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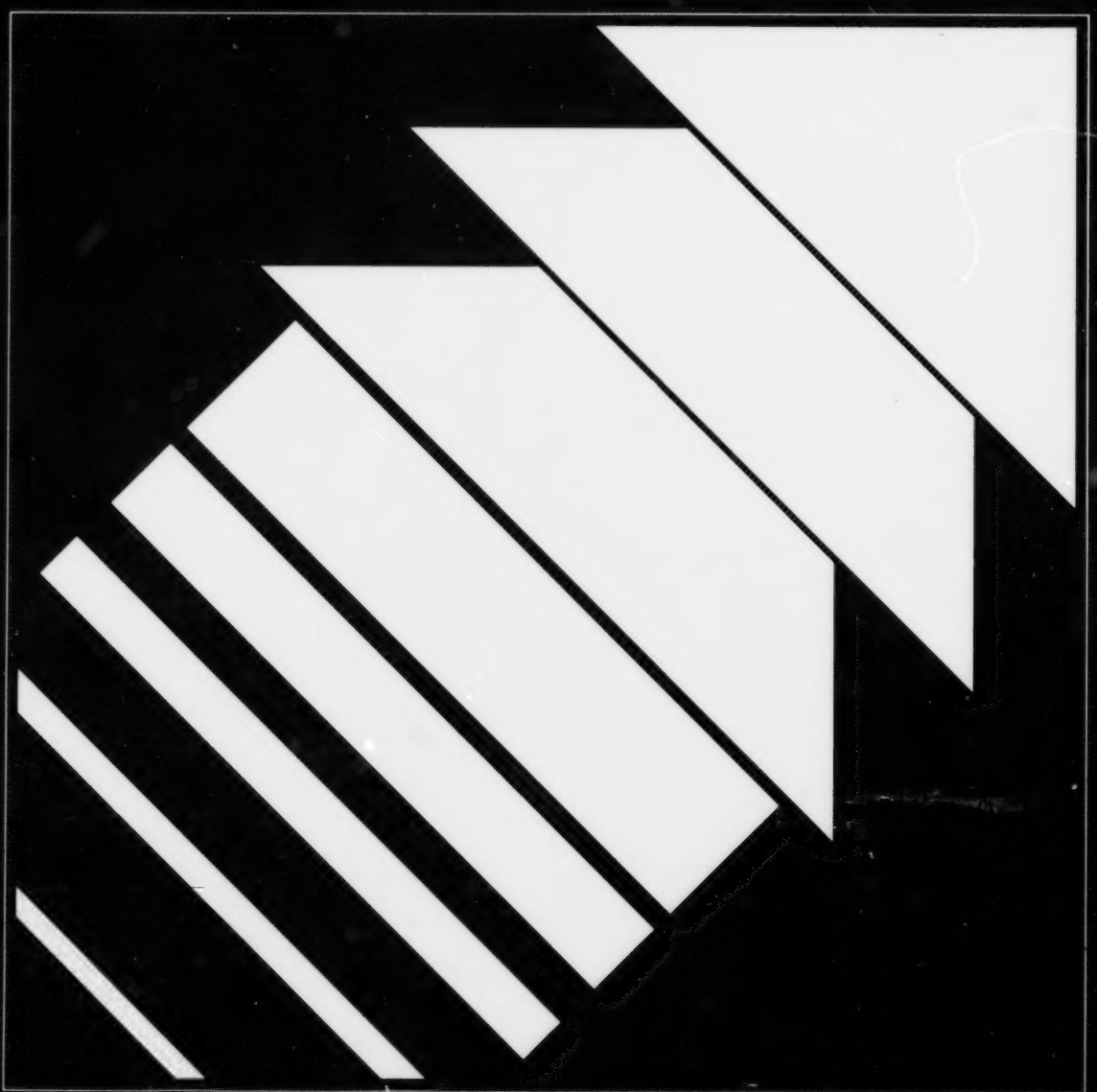

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REPORT 58901

THE TECHNOLOGY OF URANIUM TAILINGS COVERS

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Prepared for:

NATIONAL URANIUM TAILINGS PROGRAM

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THE TECHNOLOGY OF URANIUM TAILINGS COVER

"The contents of this report may reflect the views of the contractor and not necessarily the official views or policies of the Canada Centre for Mineral and Energy Technology or the National Uranium Tailings Program"

Ottawa, September 1986

REPORT 58901 - THE TECHNOLOGY OF URANIUM TAILINGS COVERS

EXECUTIVE SUMMARY

This report presents a summary of a review undertaken on behalf of the National Uranium Tailings Program on the technology of earth covers for inactive uranium mill tailings in Canada.

Covers are considered for uranium tailings impoundments for a variety of reasons:

- **Environmental protection:**

  To contain the tailings solids and leachable contaminants and prevent their distribution into the environment via surface erosive forces and leaching.

- **Aesthetics and Land Use Restoration**

  To re-establish a surface topography and vegetation or ground cover which would mitigate the aesthetic impact of the tailings deposit and permit an appropriate long term land use of the deposit surface.

- **Prevent Intrusion**

  To provide a physical barrier to prevent intrusion into the tailings by man and animals.

A primary objective of cover placement is to achieve conditions which enable the tailings to be closed-out without active care or maintenance in the long term.

Installed covers differ in effectiveness depending on the nature of the materials used and the manner in which they are placed. They also suffer long term degradation under the slow but perpetual action of erosion weathering and other disruptive forces. Their effectiveness is therefore of interest not only in the short term but for the long term. Engineering and construction technology is available to reasonably anticipate conditions and design covers for periods of 100 to 200 years duration, though periods of interest may extend beyond this to 1000 to 2000 years.

While cover placement may be considered desirable, it is often difficult to achieve in suitable form. Where the tailings impoundment surface is soft and untrafficable by conventional earthmoving equipment, placement may be not feasible or extremely costly. Tailings impoundments are also subject to surface deformations due to consolidation settlement, frost heave and a number of other causes. Such deformations require appropriate shaping of the impoundment surface profile prior to cover placement and may cause cover distortion and failure. Surface preparation can be the major cost and a major limitation in the feasibility of cover placement.

Existing abandoned deposits must be prepared for cover placement starting with the abandonment profile and doing all earthworks for shaping as part

of the close-out measures. The tailings placement system, in operating impoundments, can be modified as the impoundment approaches completion to achieve a more favourable surface shape, considerably reducing cover placement costs.

The NUTP commissioned this study with a view to evaluating available uranium tailings cover technology and determining its applicability to Canadian uranium tailings deposits. The study comprised:

- a description of Canadian uranium tailings deposits and a review of the long term stability concerns relating to surface covers and releases

- a review and description of available technology for cover design and long term stability evaluation

- application of the available technology to three generic Canadian uranium tailings structures representative of:

  (i) Elliot Lake tailings deposits
  (ii) Saskatchewan neutral generating tailings from medium grade ores
  (iii)Saskatchewan nickel, arsenic, clay tailings from high grade ores

- an evaluation of alternative cover types which may be considered at the generic sites with a view to identifying suitable cover types and technology. The following cover types were evaluated:

(a) No earth cover

  (i) no action
  (ii) contour surface and direct vegetation
  (iii) 1 m of pyrite free tailings, contour and vegetation

(b) Thin cover

  (iv) 600 mm soil cover
  (v) 600 mm rock waste cover
  (vi) 600 mm water cover

(c) Thick cover

  (vii) 3 m soil cover
  (viii)3 m layered cover
  (ix) 3 m water cover

These combinations reflect only a small selection of options that may be considered and serve mainly to demonstrate the application and results of the technology. More advantageous alternatives may exist for any specific site.

Evaluation of conditions at the existing sites suggested that the primary long term concerns regarding cover stability and release rates related to the following:

(i) Sheet erosion by water
(ii) Gully erosion by water
(iii) Wind erosion
(iv) Salt migration
(v) Differential settlement
(vi) Infiltration
(vii) Frost heave
(viii) Radon emanation

Of these, erosion, infiltration and frost heave were identified as major long term release concerns.

The alternative cover types and generic sites were analyzed and the following conclusions reached.

1. The climatic, tailings and site characteristics at the Canadian uranium tailings deposit are significantly different from those in the U.S.A. Major differences are precipitation, ore grade and contaminant contents, potential for permafrost aggradation, and climax vegetation. While much of the U.S.A.-developed cover technology is of direct relevance to Canadian deposits, a different design emphasis and some different design techniques are required for Canadian conditions.

2. The higher average moisture contents as well as effects of frost in Canadian soils reduce radon emanation and this, combined with the remote location of many of the sites, makes the suppression of radon emanation a less critical concern in the development of the design methodology.

3. The climax vegetation at the deposit sites is forest. Forest cover is therefore potentially a realistic long term stable regenerative cover. It provides erosion control and assists in limiting infiltration, frost heave and salt migration. Forest cover permits a reduction in the thickness of other cover layers which may be used in combination with it and should be evaluated in the development of all cover designs.

4. An abundance of surface water, as well as the advantages of a deep water cover, makes the use of water cover a viable and potentially advantageous cover type in Canada. Use of water cover will be limited to those sites with appropriate conditions. These conditions may only be achieved if an appropriate site location is identified at the time of tailings impoundment site selection and design.

5. Frost heave can cause severe disruption of the tailings cover and tailings releases in the Saskatchewan deposits. Canadian tailings are highly frost susceptible and cover depths to 3 m may be required to prevent frost heave. Forest cover considerably reduces the potential for frost development.

6. Infiltration is a major concern in cover design. Net infiltration must emerge as contaminated seepage. Thus the primary control of seepage release in the long term is by infiltration control by the cover. The use of low permeability infiltration barrier layers without a drainage layer above it is inappropriate as it results in high infiltration and saturated cover soils unsuitable for forest cover maintenance. In Saskatchewan the use of infiltration barrier layers appear to decrease infiltration only marginally when compared with forest cover.

7. Rock waste covers enhance infiltration and do little to improve radon emanation or frost-action. Where forest cover can be established for erosion protection there appears to be little advantage in the use of a rock waste cover. Rock waste or riprap is an essential part of cover design for gully erosion control along concentrated water flow channels.

8. The technology for the development of an economic cover layer which will support forest vegetation on reactive uranium tailings is not adequately developed. Additional research and development may result in substantial economic benefits. In the absence of such technology the use of salt migration barrier layers and soil cover may be necessary.

9. There is relatively little data available on the characteristics of the deposited tailings from the high grade nickel/arsenic, clay Saskatchewan ores. Assessment of the cover methodology and technology for these deposits will require re-evaluation as additional data becomes available. The use of moderate to thick earth or water covers appears necessary for these tailings deposits.

10. Forest cover, without or with thin unlayered earth covers appears suitable for all Canadian uranium tailings deposits from low/medium grade ores. The earth cover layer may be needed to achieve stable forest cover. Any such earth layer may be sufficient to prevent direct radiation and radon emanation to acceptable levels.

11. A flow diagram is presented which describes the evaluation and design steps required for the evaluation of alternative cover types and the design and optimization of the favoured alternative. Provision is made for the evaluation and design of cover layers (erosion barriers), radon barriers, bio barriers and liners. While such provision is made, it is the authors opinion that many, if not most, of the Canadian uranium tailings impoundments will be able to develop and implement close-out cover measures, which will be stable in the long term, without constructing most of these barriers.

This report is a summary report and is supported by more detailed documentation in five Technical Memoranda as follows:

TMI - CANADIAN URANIUM TAILINGS DEPOSITS AND STRUCTURES

TMII - CHARACTERISTICS RELEVANT TO RELEASES OF THREE GENERIC CANADIAN URANIUM TAILINGS SITES

TMIII - METHODOLOGY FOR STABILITY AND RELEASE RATE EVALUATION

TMIV - ASSESSMENT OF ALTERNATIVE EVALUATION METHODS AND ALTERNATIVE STABILIZATION PRACTICES

TMV - EVALUATION OF COVER AND STRUCTURE STABILITY OF THREE GENERIC CANADIAN URANIUM TAILINGS SITES

This study was done in parallel with another entitled "THE STABILITY OF CONTROL STRUCTURES FOR URANIUM MILL TAILINGS". The problems of stability of uranium tailings covers and structures overlap and are interdependent, with the result that the technologies are essentially similar, as are many of the concerns and conclusions.

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REPORT 58901 - THE TECHNOLOGY OF URANIUM TAILINGS COVERS

1.0 COVER OBJECTIVES AND TYPES

1.1 INTRODUCTION

This report presents a summary of the results of a review undertaken on behalf of the National Uranium Tailings Program on the technology of earth covers for inactive uranium mill tailings in Canada. The scope of the work was to:

- Describe the surface and hydrology characteristics of uncovered uranium tailings deposits in Canada.
- Based on available information, describe the characteristics of three uncovered sites (two typical of Saskatchewan deposits and one of Elliot Lake deposits) with respect to release of contaminants of concern.
- Review Canadian and international practice for establishing covers and quantify the benefits.
- Describe the technology of several reasonable types of covers for Canadian uranium mill tailings.
- Determine the environmental and cost implications of the selected cover technologies.
- With the Scientific Authority select an Elliot Lake region site and Northern Saskatchewan region site for more detailed study.
- Evaluate and discuss the application of the selected cover types to the two specific sites.

This study was undertaken in combination with a similar review and evaluation of the stability of uranium tailings control structures. A detailed description of the study has been presented in a series of five Technical Memoranda (TM) as follows:

TM I - Canadian Uranium Tailings Deposits and Structures

This technical memorandum provides a brief description of the environment at the location of the various Canadian uranium tailings deposits and the characteristics of the tailings and deposits. The purpose of the description is to provide a general understanding of the nature and variety of uranium tailings deposits and the conditions in which they exist. The stability of the existing tailings control structures and contaminant release rates are briefly reviewed. An assessment is made of the present and long-term potential for cover and structure instability on a purely qualitative basis.

TM II - Characteristics Relevant to Releases of Three Canadian Uranium Tailings Sites

The characteristics of the tailings deposits and retention structures for three typical but non-specific generic tailings sites are described. One site is typical of the Ontario deposits near Elliot Lake and two are typical of the Saskatchewan deposits for the following ore types:

- low/medium grade, low sulphide ores
- higher grade, high clay, nickel and arsenic ores

The evaluation studies undertaken in TM V are based on the characteristics defined for these three generic sites.

TM III - Methodology for Stability and Release Rate Evaluation

Available technology, that may be employed to evaluate the stability of uranium tailings covers and control structures, and to determine release rates, is described and reviewed.

TM IV - Assessment of Alternative Evaluation Methods and Alternative Stabilization Practices

This technical memorandum describes alternative cover technology, the assessment work done on alternative methods of long term stability evaluation and release rate estimation. In it the methodologies described in TM III are applied to typical Canadian deposits and structures with the object of determining the suitability and applicability of the technology to Canadian conditions.

TM V - Evaluation of Cover and Structure Stability on Three Generic Canadian Uranium Tailings Sites

The long term stability of the covers and structures of the three generic sites described in TM II are evaluated, with a view to identifying the failure mechanisms of greatest concern and appropriate long term stabilization measures. Characteristics of the generic sites, while typical of actual sites are modified to allow evaluation of a wider range of long term stability concerns under a number of reclamation scenarios and do not reflect evaluations of any actual Canadian deposits.

This study was done in parallel with another entitled "The Stability of Control Structures for Uranium Mill Tailings" and written up in a report of the same title (Steffen Robertson & Kirsten, 1986). The problems of the stability of uranium tailings covers and structures overlap and are interdependent. Consequently the technologies are similar and there is a considerable amount of repetition in the two reports which have been prepared as independent documents.

1.2 STUDY OBJECTIVES

During the past 15 years there has been a marked increase in the concern and interest by the public, regulatory authorities and the mining industry in the environmental impact of uranium and other mine wastes. Uranium mine wastes and tailings, because of their radiological constituents, have been the focus of many of these concerns. An early reflection of public concern in Canada, and a key document in the process of Regulatory control of uranium tailings is the Final Report of Cluff Lake Board of Enquiry (Bayda, et al, 1978). This enquiry investigated the environmental impact of both the Cluff Lake mine development as well as future uranium mining development in Saskatchewan. The effects of tailings and mine wastes were a major component of this enquiry.

As a consequence, considerable effort has been made by both industry and Regulatory Agencies alike to develop and implement adequate stabilization and control technology. The objective of this technology is to isolate or stabilize the tailings in the depository area. Release rates of environmental contaminants must be sufficiently low to satisfy release criteria which ensure that an acceptable level of environmental impact is achieved in both the short and the long term.

During the operating period, while tailings are being produced, manpower and equipment resources are available at the mine site to monitor the release rates. If release rates exceed specified limits, remedial action can be implemented. Following closure of the mill facilities, the tailings deposits remain as a long term potential source of radioactive materials and other environmental contaminants. The rate at which these contaminants may be released to the environment will change with time as:

(i) the tailings change their chemical and physical nature as a result of the weathering and other hydrogeochemical processes that occur, and

(ii) the containment control structures are subject to physical and chemical processes which modify their ability to function in the manner in which they were originally conceived and designed.

If the rates of change are very, very small then the changes in the release rates may not be significantly different for a very long time. Small but perpetual change which results in cumulative increases in release rates may bring about unacceptable rates of release in lesser time periods. Rapid changes could result in large releases in relatively short periods.

Critical to an evaluation of the long term environmental impact of uranium tailings is the stability of both the tailings products and the containment structures. Stability is that characteristics of a material or structure which indicates its resistance to change. A structure or material is stable if, over the period of interest, the change in it is sufficiently small not to make a material difference to the rate of the contaminant releases with which it is associated. Conversely, it is unstable if the release rate changes materially or becomes unacceptably high.

The tailings materials themselves are metastable in that they have been crushed and placed in an environment which differs considerably from that existent at the location of the original ores. Considerable change may occur in the physical and chemical nature of the tailings before they reach equilibrium under the conditions of this new environment.

Most of the physical and chemical change of concern to the long term stability of uranium tailings and their containment structures are relatively slow but progressive. It is necessary to know both the rate of change and the time period of interest before an assessment can be made of the long term stability of the materials and structures.

The period for which the tailings will remain as potential contaminant sources exceeds by a number of orders of magnitude the periods for which man can economically design and construct tailings containment structures. Thus the period of interest is determined by that period over which current design and construction technology can be applied with some confidence.

At the onset of this study it was presumed that current design and construction technology should be able to achieve stable structures over periods of at least 100 to 200 years. Since the purpose of this study is to evaluate the long term stability of such structures, an evaluation period extending to between 1000 and 2000 years into the future was selected.

The main objective of this study was to identify the available technology for cover design and then to perform an evaluation of the long term stability of alternative covers.

1.3 SELECTION AND DESIGN OF COVERS

1.3.1 Cover Types

Four basic cover materials can be considered:

- vegetation
- soil cover
- waste rock or riprap covers
- water cover

Each of these cover materials has advantages with respect to tailings isolation and long term stability. Some of the advantages and disadvantages are given below:

(i) Vegetation Cover

Advantages:

- low cost if easy to establish
- regenerates (self maintains)
- good wind and sheet erosion protection (erosion barrier)
- helps control upward salt migration
- can help to control infiltration
- reduces frost action in tailings

Disadvantages:
- may not be possible to establish on phytotoxic tailings
- roots penetrate low permeability layers and clog drainage layers
- will not entirely control gully erosion
- may increase infiltration
- does not inhibit radon emanation

(ii) Soil Cover

Advantages:
- cheapest layer material
- good radon control (radon barrier)
- can reduce infiltration (infiltration barrier)
- can support vegetation

Disadvantages:
- higher cost than vegetation
- erodible unless vegetated
- frost susceptible
- permits salt migration

(iii)Waste Rock or Riprap Cover

Advantages:
- excellent sheet and gully erosion resistance (erosion barrier)
- inhibits salt migration (salt migration barrier)
- serves as drainage layer

Disadvantages:
- high cost, if mine waste not available
- increases infiltration
- poor radon inhibitor

(iv) Water Cover

Advantages:
- good radon inhibitor
- prevents erosion
- prevents acid generation

Disadvantages:
- shallow depths (< 2 m) not suitable
- seasonal fluctuations
- may increase infiltration
- may become contaminated

In order to achieve the long term stability characteristics required, it may be necessary to design and install covers which employ a combination of these cover materials. For example, a soil cover which serves as both a radon and infiltration barrier may have vegetation installed on it to provide erosion and frost action controls.

1.3.2 Selection and Design of Surface Covers

The most cost and environmentally effective surface cover appropriate for any particular tailings deposit depends on a wide range of site specific factors. These include, but are not limited to, the nature of the tailings and associated pollutants, topographic, climatic and soil conditions, sensitivity of the surrounding environment, potential for revegetation or a

water cover, and the availability of rock material. An approach to the selection and design of surface covers has been proposed by Beedlow, 1984. A modification of the flow diagram he proposed, which allows for water covers and the evaluation of infiltration, salt migration and frost heave is shown in Figure 1.

This flow diagram is fairly simplistic and does not allow for all the combinations or variations in cover types. It does serve to illustrate the data collection, evaluation and design process. The following description is a modification of that proposed by Beedlow.

Phase one consists of evaluating site conditions. For a given site, data on tailings, climate, soils, hydrogeology, geomorphology, and vegetation are collected. The long-term vegetative potential for the site may then be determined by evaluating existing vegetative cover on soils that are available and desirable for use at the site. Expected climatic changes also need to be considered. Over the long-term, vegetation on the covered tailings can be expected to resemble that in the surrounding area where soils drainage and topography are similar. Therefore, the erosion rate of vegetated soils may be calculated. Site data on vegetation, climate, soils, and geomorphology is used to determine the erosive forces acting on the cover. Areas exposed to channel flooding or gully erosion may need riprap or other forms of engineered armour. Those not exposed to flooding and gullying can probably be stabilized by vegetation and/or unengineered rock covers. Based on the calculated erosion rates and criteria for stability, the adequacy of vegetation for surface protection can be determined.

In Canada, the potential of a long term stable water cover may be evaluated as an alternative to vegetation. The potential of a water cover, as an economic alternative to vegetation, is dependent on having appropriate topographical conditions and excess water. The economic viability of such a cover should become apparent with a minimum of design and costing.

Determining the adequacy of vegetation is appropriate, because even if no surface treatment is applied, vegetation will become established in time. It may be possible to achieve vegetation cover in acceptably short-time periods by simple measures such as contouring, draining and seeding of the tailings. More complex actions such as chemical treatment of the surface tailings layers may still be more cost effective than cover placement. If vegetation is considered adequate, a preliminary revegetation plan is produced. If vegetation is judged to be inadequate for long-term erosion control on all or parts of the pile, other means must be used to prevent erosion damage. The next step is to determine the need and cost of suitable rock for covering the entire pile or portions of the pile exposed to high erosion rates, but they may not be available locally. The cost of using rock covers is heavily dependent upon the cost of excavating or quarrying and the distance it must be hauled. At some distance rock may no longer be affordable.

If rock cover is feasible, a preliminary design using rock or a combination of rock and vegetative covers can be produced. If suitable rock is not available, the use of additional overburden, greater amounts or better quality topsoil, or recontouring the pile may reduce erosion rates. Once

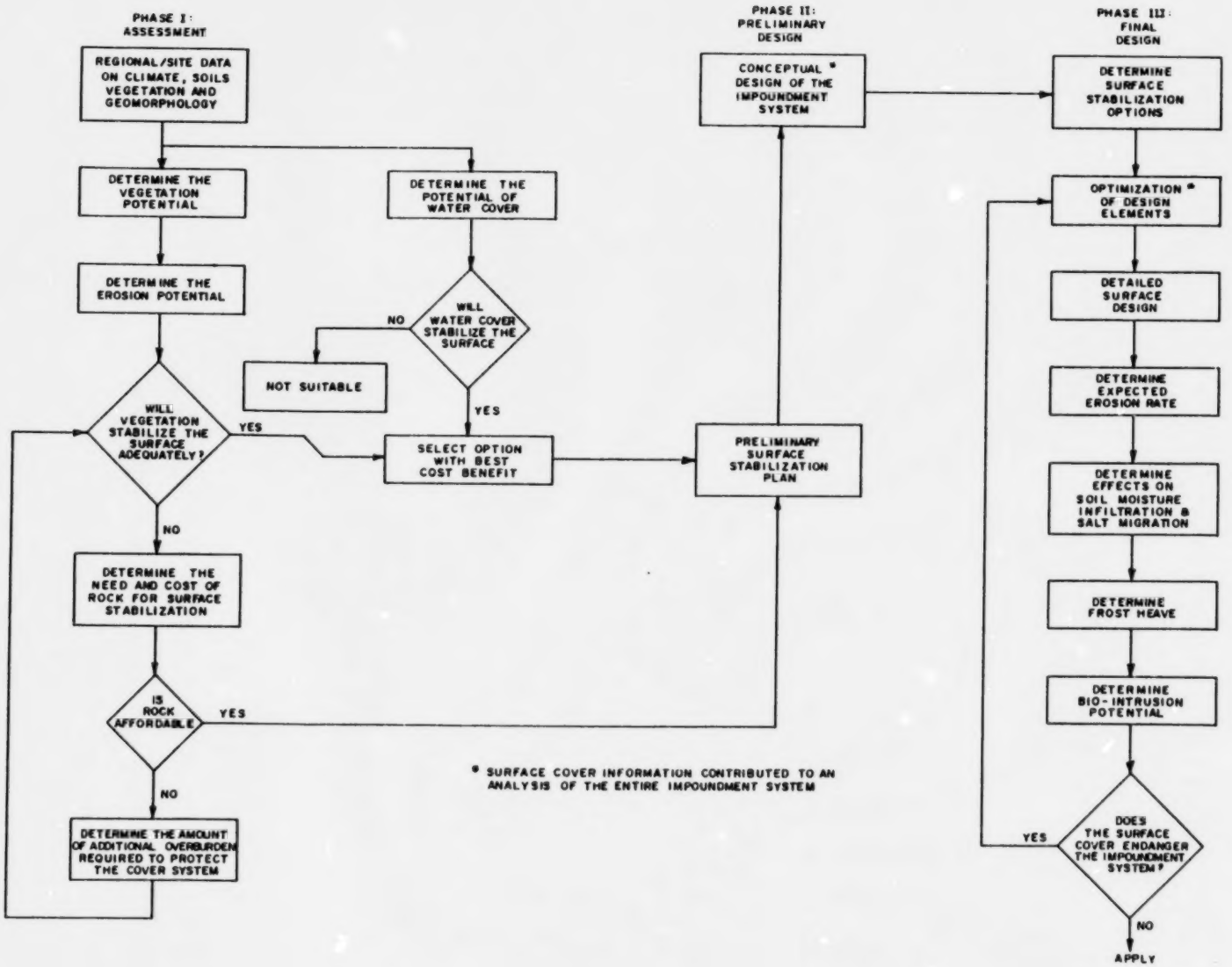


FIGURE 1

FLOW DIAGRAM FOR DESIGNING INACTIVE MILL TAILINGS SURFACE COVERS (AFTER BEEDLOW, 1984, MODIFIED TO INCLUDE WATER COVERS, INFILTRATION, SALT MIGRATION AND FROST HEAVE).

these options are determined, erosion potential is recalculated and again the adequacy of vegetation as a surface cover is evaluated. This process may require several iterations before a preliminary plan is produced.

The preliminary surface stabilization plan is intended to provide information and alternatives for surface cover design to those planning radon barriers, bio barriers and liners (if tailings are moved). Once the overall containment system concept has been approved, a final design for surface covers can be produced.

While provision is made in the flow diagram for the design of cover layers, radon barriers, bio barriers and liners, this does not imply that they are needed for the adequate stabilization of any particular tailings deposit in Canada. Indeed it is the authors' opinion that many, if not most, of the Canadian uranium tailings impoundments will be able to develop and implement close-out cover measures, which will be stable in the long term, without constructing most of these barriers.

The third phase of the design process begins by determining the options for surface stabilization available for the site. The cost and effectiveness of the alternatives are optimized in conjunction with other containment system components. Before the final design can be chosen, impacts of surface stabilization design on the functioning of the entire system must be evaluated in detail. Erosion rates are determined using site environmental data and engineering specifications. Effects of surface covers on infiltration soil moisture and salt migration should be determined, taking radon and biological barrier designs (and liners when appropriate) into account. Frost heave must be evaluated as this is crucially dependent upon cover type. The risk, and possible effects of plant and animal intrusion resulting from the proposed surface cover must be evaluated at this time. If the consequences of surface cover design do not jeopardize the functioning of the system based on the above evaluations, then the design can be finalized. If the surface cover does jeopardize the functioning of the system, then alternative designs are considered. Again, several iterations of this process may be necessary.

The major benefit of the flow diagram approach is the flexibility it allows in designing surface covers. It does not specify types and amounts of cover material but requires only that designs provide adequate surface erosion control and not jeopardize the containment of toxic compounds. Adequate erosion control is, logically, that which is required to keep the protective layer intact for the design life of the containment system. A surface cover, therefore, can be any combination of untreated tailings, treated tailings, water, soil, rock and vegetation that is effective and economical.

1.4 EVALUATION FOR CANADIAN CONDITIONS

1.4.1 Characteristics of Canadian Deposits

Sources of available technology for cover design have been reviewed in section III.1.2 of Technical Memorandum III. Much of the available technology and recommended design methodology is based on research undertaken in the United States of America as a consequence of the U.S.

Congress enactment of November 1978 entitled the Uranium Mill Tailings Radiation Control Act. The standards, guidelines and recommendations resulting from this research are suited to the ore types, climatic conditions, problems and concerns typical of the U.S.A. uranium tailings deposits.

These conditions are materially different from those applicable to the Canadian uranium tailings deposits. A direct transfer of the standards, methods and guidelines, developed for the U.S. deposits, to the Canadian deposits is inappropriate. However, much of what has been done in the U.S.A. and elsewhere is of direct relevance, or can be modified to be applicable, to Canadian deposits.

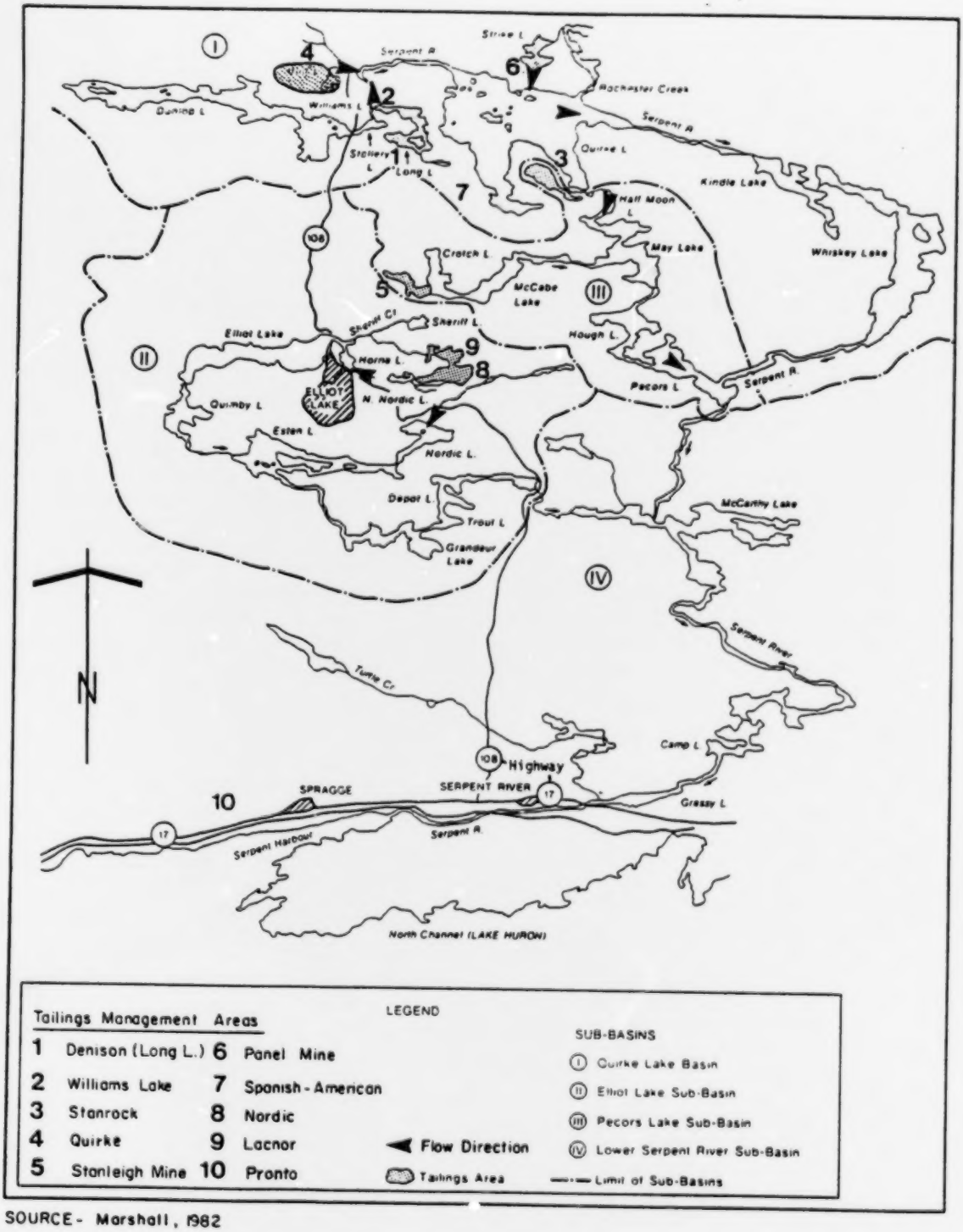
In order to identify these differences, a review was made of all Canadian uranium tailings deposits and a description developed of each of the deposits. This description is presented in Technical Memorandum I.

Almost all the Canadian uranium tailings are located in deposits in two geographical areas. Approximately 100 million tons of tailings from 13 mines and 11 mills have been produced and placed in 10 deposits in the Elliot Lake region of Ontario. The location of these tailings areas are shown on Figure 2. The second major uranium mineral belt occurs in northern Saskatchewan where 10 mines (now all decommissioned) operated in the Uranium City area. Three new mines have been started since 1975 at Cluff Lake, Rabbit Lake and Key Lake. All these deposits are located north of 57th parallel as shown on Figure 3.

Some of the major differences between typical Canadian and typical U.S.A. deposits are reviewed below.

(i) The topography and geomorphology for all Canadian sites (described in I.2.1 of TM I) is fairly similar as both areas are located on the Canadian Shield. The topography is characterized by bedrock knolls and ridges separated by lower areas consisting of numerous lakes and swamps. While the bedrock geology differs in the various areas, there is generally only a shallow surficial cover of glacial tills and outwash sands, with recent organic deposits (muskegs). These areas are generally deficient in clay deposits. This contrasts strongly with most of the U.S.A. deposit areas where deep soils often overly the bedrock. These soils are rich in clay minerals, and therefore have a high ion exchange capacity making them very active retardants of many forms of contaminants in the tailings seepage water.

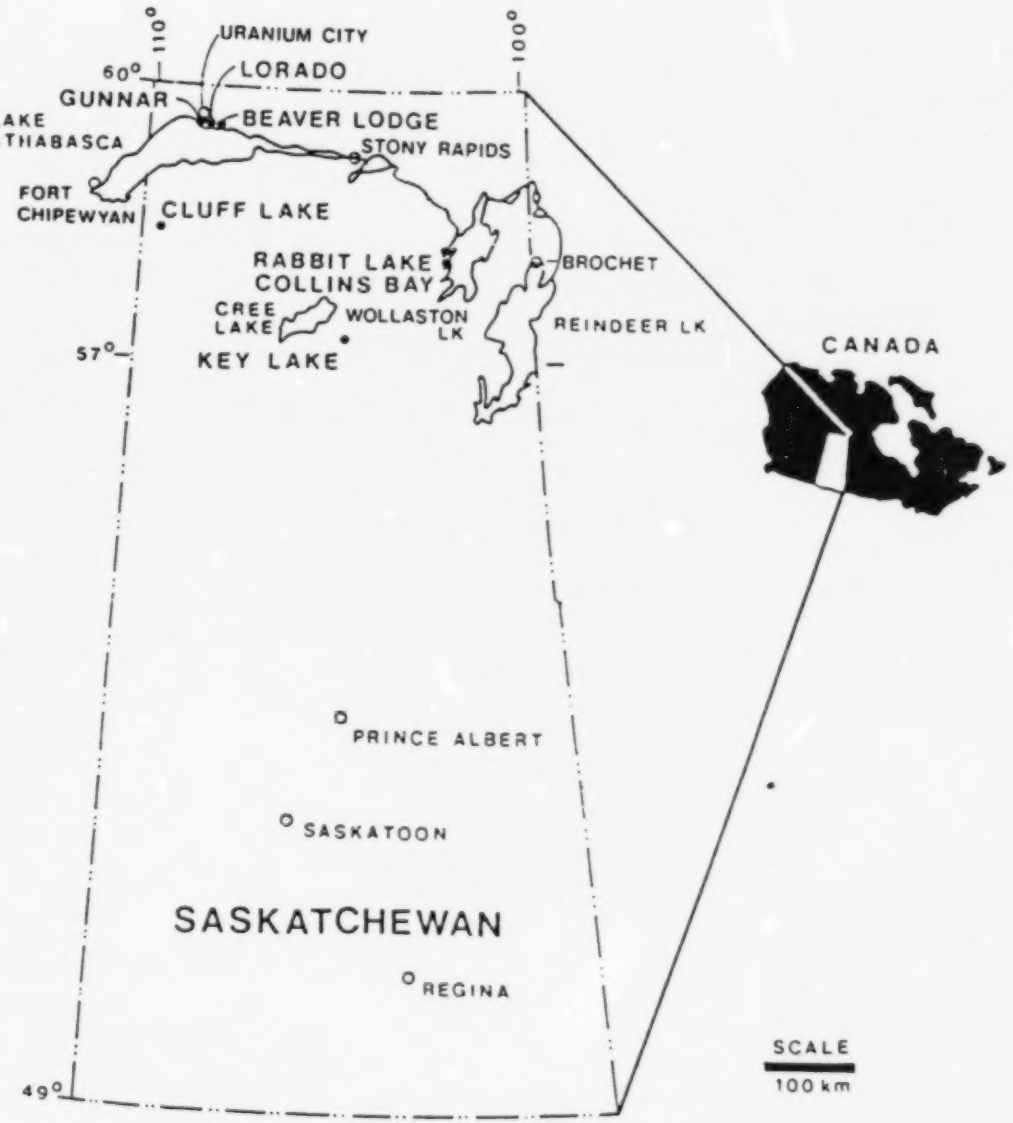
(ii) The water table at the Canadian sites is generally shallow. Infiltration and seepage is generally very active (short seepage path lengths and rapid seepage) and the ground and surface waters are of a high quality with a low concentration of dissolved solids. This contrasts with typical U.S.A. sites where groundwater tables are often at depth with low rates of recharge and seepage migration. Thus the impact of contaminated seepage from U.S.A. deposits are typically considerably less than from Canadian deposits.



SOURCE - Marshall, 1982

TAILINGS MANAGEMENT AREAS, ELLIOT LAKE, ONTARIO

FIGURE 2



TAILINGS MANAGEMENT AREAS, SASKATCHEWAN

FIGURE 3

(iii) An excess of precipitation over evaporation occurs in the Elliot Lake area compared with deficits in Saskatchewan and most of the U.S.A. deposit areas (Refer I.2.2). The design of zero discharge systems are therefore not possible at Elliot Lake. The large surface runoff from all Canadian deposit areas and the abundance of surface water makes it feasible to consider water cover as a viable cover option.

(iv) Infiltration and soil moisture is generally considerably greater for the Canadian sites than for U.S. deposits. This has beneficial effects:

- The increased soil moisture results in decreased radon emanation rates (refer section IV.1.4). Radon emanation rates (for equivalent tailings deposits) are considerably less in Canada than the U.S.A. and therefore of less concern.

- Vegetation can be more easily established than in the drier U.S.A. deposit areas.

It also has disadvantages:

- All infiltration becomes contaminated and must emerge as contaminated seepage.

- Mounding of the water table occurs in some impoundments resulting in flooding (and vegetation kill) as well as upward leaching and salt migration.

(v) Greater frost potential and freezing depths occur at the Canadian sites. Discontinuous permafrost conditions exist at all the Saskatchewan sites, where frost heave is a potential cause of cover instability.

(vi) Forest type vegetative covers are characteristics of both the Elliot Lake and Saskatchewan tailings areas (Refer I.2.3). If similar vegetation can be established on the uranium tailings deposits then they form a much more effective erosion protection layer than can typically be achieved by the sparse grass and scrub type covers considered more typical of the U.S.A. tailings areas.

(vii) A lower incidence of burrowing animals, especially colony types, occurs in the Canadian deposit areas than in the U.S.A. (Refer I.2.4). Sites also tend to be more remote from human habitation areas (Refer I.2.5). Thus the potential for burrowing or excavation is less with a commensurately lower requirement for biotic barriers.

(viii) Ore characteristics vary greatly even between the various Canadian deposits. Three broadly different ore types can be identified in Canada (I.3.1):

(a) Lower grade ore, high pyrite tailings from the Elliot Lake ores. These tailings are acid generating resulting in both acidic seepage and salt migration. This acid generating potential makes direct revegetation problematic and requires long term seepage water control.

(b) Low/medium grade ore, non-acid generating tailings from the majority of the Saskatchewan mines. These tailings have a relatively low environmental impact potential.

(c) High grade ores, sulphide, nickel-arsenic tailings from the newest Saskatchewan mines which have acid generating potential, and relatively high environmental impact potential as a consequence of the contained radionuclides, nickel and arsenic. A higher level of isolation and contaminant security is required for these tailings than for those above, or for typical U.S. deposits.

Unlike most U.S.A. uranium tailings deposits, the Canadian tailings are generally neutralized or taken to a high pH prior to discharge. The potential for low pH conditions are therefore dependent on the acid generating potential of the tailings and the development of conditions which will result in acid generation in the deposit.

In order to identify the characteristics of Canadian deposits relevant to contaminant releases and long term stability, a summary description was prepared for most of the major deposits including 9 in the Elliot Lake area and 6 in northern Saskatchewan (refer section I.4). The materials used for construction and construction practice have a considerable effect on the effectiveness and long term stability of the impoundment facilities and these were summarized for various representative Canadian sites (refer section I.6).

1.4.2 Instability and Release Mechanisms

The principal mechanisms of instability which may result in changes in release rates have been identified as follows:

- sheet erosion
- gully erosion (including flood erosion)
- wind erosion
- biological penetration
- salt migration/weathering
- differential settlement
- frost heave
- infiltration (hence seepage)

Any of these failure mechanisms could result in increased releases in the form of:

- particulate transport
- contaminated seepage

- radon emanation
- direct radiation

Based on the information available to the authors in the available documentation as well as discussions with some of the deposit operators and involved persons, a qualitative assessment was made of the potential for tailings cover instability, assuming that a minimal amount of cover preparation is done at each site at close-out. Both present and future instability was considered. The results of this assessment (refer I.6.11) are summarized in Table 1. It should be noted that this evaluation of present or future instability does not imply that the potential for tailings releases will remain as evaluated. In many instances (including all operating impoundments) the facility operator may implement maintenance, secondary containment or alternative close-out measures which considerably modify and possibly prevent any instability or releases. The assessments are subjective and are made without knowing what final reclamation work and cover placement will be implemented. It serves to provide an assessment of those potential mechanisms of failure most likely to result in instability of covers on Canadian uranium tailings deposits.

From these evaluations the following conclusions were reached:

o Because of the great similarity in tailings surface conditions of the Ontario deposits they have very similar potentials for instability. Saskatchewan sites display a much greater variability of potential.

o Sheet erosion is presently considered a cause of only minor instability on all sites except the Gunnar and Lorado sites, where it is severe. The potential for sheet erosion increases to the moderate and severe categories for the long term for most sites.

o Presently gully erosion ranges from minor through severe and becomes severe for almost all sites in the long term.

o Wind erosion is presently considered minor except for Gunnar and Lorado where it is severe. Assuming vegetative cover, wind erosion will remain minor to moderate in the Elliot Lake region but is considered potentially severe on all the Saskatchewan sites.

o Salt migration is currently only of concern at Lorado and Stanrock but is expected to become moderate to severe at all sites except Key Lake and Collins Bay.

o Differential settlement is of minor concern presently and is expected to become a major potential cause of cover instability only at Rabbit Lake and Gunnar.

o Frost action and heave is considered a minor problem both for present and future conditions in the Ontario deposits. Moderate to severe potential instability is anticipated in the long term for all the Saskatchewan deposits except Collins Bay.

o Infiltration, as a source of seepage water, is considered to be a moderate to severe potential instability at all sites.

TABLE 1

SUMMARY OF ASSESSMENTS OF POTENTIAL INSTABILITY OF IMPOUNDMENT SURFACES
(see note (iii))

IMPOUNDMENT SITE	MODE OF INSTABILITY															
	Sheet Erosion		Gully Erosion		Wind Erosion		Salt Migration		Differential Settlement		Frost Heave		Infiltration	
	P	F	P	F	P	F	P	F	P	F	P	F	P	F
A. ONTARIO SITES														
Denison Tailings	m	M	m	M/s	m	M	n	M	m	m	m	m	m/M	M
Williams Lake Tailings	m	M	m	M/s	m	M	n	M	m	m	m	m	m/M	M
Stanrock Tailings	m	M	M	M/s	m	m	M	M/s	m	m	m	m	m/M	M
Quirke Tailings	m	M	m	M/s	m	M	m	M	m	m	m	m	m/M	M
Stanleigh Tailings	m	M	M	M/s	m	m	m	M	m	m	m	m	m/M	M
Panel Tailings	m	M	m	M/s	m	m	m	M	m	m	m	m	m/M	M
Spanish American Tailings	m	M	m	M/s	m	m	m	M	m	m	m	m	m/M	M
Lacnor & Nordic Tailings	m	M	m	M/s	m	m	m	M	m	m	m	m	m/M	M
B. SASKATCHEWAN SITES														
Cluff Lake Tailings	N	M/s	N	M/s	N	M/s	N	m/M	N	M	N	M	N	M/s
Key Lake Tailings	m	s	m	s	m	s	n	m	m	m	m	m/M	m/M	m/M
Rabbit Lake Tailings	m	m	m	M	m	s	n	M	m	s	M	M/s	m/M	M/s
Collins Bay Tailings	n	m	n	n	n	n	n	m	m	m	n/M	m	m	m
Gunnar Tailings	M/s	M/s	M/s	M/s	s	s	M	M	M/s	M/s	M/s	M/s	s	s
Lorado Tailings	s	s	s	s	s	s	s	s	m	m	m/M	m/M	s	s

NOTES:

(i) P = Present conditions refers to current experience for the respective mode of instability, classed as:
- n - none
- m - minor
- M - moderate
- s - severe
- N - not applicable
- U - unknown

(ii) F = Future potential conditions refers to the potential of releases occurring over a 200 to a 2000 year period if no extensive abandonment measures are implemented, classed as:
- n - none
- m - minor
- M - moderate
- s - severe
- N - not applicable
- U - unknown

(iii) Evaluations of present or future instability do not imply potential for tailings releases. Releases can be prevented by maintenance, secondary containment or implementation of alternative reclamation measures. Reclamation measures have yet to be finalized for all operating impoundments and some of the inactive impoundments.

1.4.3 Generic Examples Evaluated

A selection of representative cover types were identified for evaluation with generic uranium tailings impoundments. The three generic uranium tailings were selected to be typical of:

(i) a tailings deposit in the Elliot Lake area

(ii) a tailings deposit typical of a Saskatchewan low sulphide tailings deposit formed by the mass discharge of tailings (Wet Tailings Site)

(iii) a tailings deposit typical of a Saskatchewan nickel/arsenic, sulphide tailings deposit formed by discharging thickened tailings in a managed layered sequence (Semi-Dry Tailings Site)

The range of representative covers were selected to cover the following:

(a) direct vegetation

  (i) with no surface preparation to serve as a base case

  (ii) with contouring and drainage

  (iii) with a 1 m deep pyrite free layer in the case of the generic Elliot Lake Site only

(b) thin cover (600 mm)

  (i) soil with direct vegetation

  (ii) waste rock

  (iii) water cover in the case of the Elliot Lake Site only

(c) thick cover (3 m)

  (i) thick soil cover

  (ii) layered cover which varied for the different sites as indicated in Table 2 and with different engineered barrier layers

  (iii) water cover

An evaluation of the stability of the alternative covers was undertaken as described in TM V. The conclusions reached as a result of these evaluations are included in the following sections of this report.

TABLE 2

ALTERNATIVE THICK (3 m) ZONED COVERS CONSIDERED

SITE	ZONE	THICKNESS (mm)	PURPOSE	MATERIAL ADDITIVES
Elliot Lake Site	Sand and gravel	1000	rooting medium	
	Till	1000	infiltration/ radon barrier	
	Sand and gravel	1000	suction break	
Wet Tailings Site, Saskatchewan	Soil	500	rooting medium	
	Waste rock	1500	drainage layer capillary break biobarrier	
	Soil-bentonite	1000	radon/infiltration barrier	4% bentonite
Semi-Dry Tailings Site, Saskatchewan	Till	500	rooting medium	
	Sand	1500	drainage, capillary break	
	Soil-bentonite	1000	radon/ infiltration barrier	4% bentonite

Total thickness 3 metres each.

2.0 COVER STABILITY AND DESIGN METHODOLOGY

2.1 SHORT AND LONG TERM DISRUPTIVE EFFECTS

2.1.1 Introduction

Cover failure can occur as a result of:

- o large short term forces such as floods, forest fires, earthquakes and extreme frost conditions. Such extreme events happen with a frequency which is generally inversely proportional to the severity of the event.

- o long term degradation which results in a significant change of the original design or design conditions. Examples are sheet erosion, clogging of drainage layers by salt precipitation or roots, weathering and breakdown of riprap armour and salt migration.

Cover failures will most probably occur as a combination of short and long term effects. For example, upward salt migration may result in the dying off of a tree cover which results in severe gully erosion during a high precipitation event.

Both short and long term disruptive effects are considered in this section. The recurrence periods or probability of occurrence of extreme events has been evaluated in section IV.2 of Technical Memorandum IV.

2.1.2 Climatic Change

Because of the long period of interest, the likelihood of extreme events occurring is proportionately large. The probability of occurrence of fires, floods, tornadoes or other extreme events, for which there is a record of smaller events, can be determined based on the probability frequency relationships that can be developed for the historical record of events. In Canada, this record is relatively short, generally not more than a few tens of years, and the extrapolation to events that have a probability of occurrence in the very long term of 1000 to 2000 years may be of questionable accuracy. Nevertheless, the methodology is relatively well defined and as the period of record increases, so will our ability to more accurately determine the probability of occurrence of extreme events.

The period of record applies to a period in which a particular climate applied. However, the earth's climate is not fixed. Evidence suggests (McInnis, 1985) that climatic cycles occur regularly, varying from relatively minor 30 year cycles to major glacial and interglacial cycles of tens to hundreds of thousands of years.

The weather of Canada in several years, or its climate a few centuries from now is unknown (Hare and Thomas, 1974). Thus the record from which the projections of extreme events are made may not be representative of the climatic conditions which may cause them over the next 1000 to 2000 years.

While it is questionable whether man has altered world climate to date, the potential for material alteration increases and his influence may rival or

overrule natural climatic changes early in the twenty-first century or sooner (Hare and Thomas, 1974).

Substantial climatic changes can cause extreme events of which there is no recent record in the Canadian uranium tailings areas, such as glaciation, extreme drought or high precipitation periods. Even relatively small changes, such as a temperature change of 2 to 3°C, could have large consequences, such as the potential for permafrost and frost heave.

Much of the work summarized in this section is taken from McInnis (1985) in which a literature review of long term natural events was undertaken for NUTP.

Glaciation

Some general characteristics of climate in the past suggest that an ice age is due (Kilborn and Beak, 1979). The probability of a transition in the next 100 years to the type of climate leading to an ice age is quoted by Pittock et al (1978) as being less than one percent. The probability of onset within the next 1000 years of glacial climate associated with the 100,000 year glacial-interglacial cycle is estimated by Lamb (1977) to be about two percent.

Greenhouse Effect

Two models (Bruce and Hengeveld, 1985 and Parry and Carter, 1984) predict some effects in Canada of the increased carbon dioxide in the atmosphere resulting from man's activities. They conclude that the temperature rise will be about 2.5°C and 2.5° to 5°C for the Saskatchewan and Ontario tailings site areas, respectively. Natural vegetation of northern Saskatchewan will change from moist boreal forest to cool temperature steppe while that at Elliot Lake will remain cool temperature forest. Since recorded data of the past century indicate that so far, no temperature rise due to carbon dioxide has occurred (Hare, 1981 and Ellsaesser, 1985), predictions should be treated with skepticism.

Climatic Cycles

Associated with the short duration climatic cycles there will be periods, for example, which are both wetter and dryer than that measured in the period of record. Shorter periods (of a few years) which are significantly wetter (wet periods) or dryer (droughts) will occur. These periods will have a major impact on such aspects as vegetational survival and the height of the phreatic surface in the tailings impoundments. Average temperature variations can be expected to result in periods of aggradation and degradation of frost, a major potential disruptive force in Canada. Since one is unable to predict such changes they can only be allowed for in a subjective or parametric way in the long term stability evaluations.

2.1.3 High Precipitation

The methodology for flood estimation has been presented in Section III.2.1.

Estimates of the high precipitation events up to the 100 year 24 hour storm event for the Elliot Lake and Uranium City (Saskatchewan) areas are given in Tables I.2.A-2 and I.2.B-4. There is a maximum flood of which the catchment basin is capable termed the probable maximum flood (PMF), which is associated with the probable maximum precipitation event (PMP). The PMP for the Elliot Lake area has been estimated at 420 mm in a 12 hour period (Pullen and Davis, 1981, and MacLaren and Golder, 1980) and about 300 mm in northern Saskatchewan (see section I.2.2.B). These probable maximum precipitation events are approximately three times greater than the 100 year 24 hour precipitation events.

2.1.4 High Winds

Tornadoes, tropical cyclones and low pressure storm systems are sources of high winds.

Tornadoes

Tornadoes do not occur in northern Saskatchewan. Elliot Lake lies in the zone of average annual tornado frequency of 0.4 to 0.8/10,000 km^2, (Newark, 1983). This demonstrates that the Elliot Lake area will be struck by several tornadoes in the 20 to 2000 year period. Though they are the most destructive of all winds, their duration at a site is too short to weaken an impoundment (Kolousek, 1984).

Tropical Cyclones

There is no record of tropical cyclones in northern Saskatchewan.

Out of 350 Atlantic tropical cyclones during a fifty year period only 25 had noticeable effects on weather in southern Ontario, and only eight caused high winds or excessive rain.

The hurricane return period at Elliot Lake is estimated at 100-200 years (Newark, 1985).

Low Pressure Systems

At the Saskatchewan and Ontario sites, damage to tailings impoundments from high winds is normally due to the low pressure storm systems that are a regular part of the weather (McInnis, 1985). In comparison, tropical cyclones pose a small threat.

Low pressure storm systems are most intense in winter. Peak gusts from thunderstorms in both tailings areas lie between 70 and 90 km/h (19.2 and 25 m/s) (McInnis, 1985).

2.1.5 Earthquakes

Dynamic loads due to earthquakes may result in the liquifaction of low density saturated tailings or uncompacted saturated portions of granular embankments or embankment foundation materials.

The Saskatchewan sites are located in a zone of relative seismic stability with a low potential for seismic accelerations at a level likely to induce slope instability or liquifaction.

In the Elliot Lake area seismic activity is low but not negligible. The "Maximum Credible Earthquake" likely to effect the area is of magnitude 6.5 on the Richter Scale (Reades et al, 1982) and is located 230 km from Elliot Lake. It is predicted that the event would cause an intensity VI effect, on the Modified Mercalli Scale, at Elliot Lake, with corresponding peak ground accelerations of 0.065g. Studies by Golder Associates, 1982, and Weston Geophysical Research Inc., 1979, on the potential of liquifaction of tailings indicate that the potential is low, and that the embankments studied would be stable.

Mining induced seismic events have been occurring in the Elliot Lake area as a result of pillar bursting and mine collapse (Hedley et al, 1984). Some of these events have exceeded magnitude 3.5 on the Richter scale. Because of the close proximity of these events, the potential exists that mining induced seismicity would possibly influence impoundment stability.

2.1.6 Forest Fires

All the uranium tailings areas are within natural forest cover areas which have been swept with forest fires at irregular intervals. Past experience is that forest fires are followed by rapid re-generation of the vegetative covers. The greatest risk associated with the temporary loss of cover is the potential for erosion, upward salt migration and frost heaving. Since forest fires may be anticipated on several, if not numerous, occasions in the 100 to 2000 year period of interest, the secondary effects may be severe.

2.2 ESTABLISHMENT AND LOSS OF VEGETATION COVER

2.2.1 Object and Methods

Forest is the climax vegetation cover for both the Elliot Lake and northern Saskatchewan uranium mining regions of Canada. Climax vegetation cover represents a comparatively stable and long-term form of cover for a region. Long-term change in the nature of a climax cover is determined by global changes in environment only (e.g., cooling or warming of the earth's atmosphere, glaciation, greenhouse effects). Man-induced destructive changes or natural catastrophes, e.g., fire or disease infestation may destroy a climax vegetation cover but they do not prevent the natural re-occurrence of the climax vegetation over time. The nature of the destruction only determines the time rate at which the climax vegetation will be re-established.

The major advantages to the establishment of a forest cover in both regions are two-fold.

1. Forest cover is self-perpetuating and maintenance-free as well as exhibiting long-term persistence and stability.

2. Forest cover is a prime form of surface water runoff, wind and water erosion control. It also effects the soil moisture which assists with radon emanation control, salt migration control and infiltration.

A vegetation cover design guide has been prepared for U.S. uranium tailings deposits by Beedlow, 1984. Combination covers such as those illustrated in Figure 4 are considered. This design guide, while it illustrates and discusses many of the aspects relevant to vegetation cover design is not of direct application to Canadian uranium tailings deposits.

Uranium tailings abandonment procedures in the western United States have not considered the establishment of a forest cover as a final vegetation cover. The climax vegetation cover for the uranium producing areas of the western United States is grassland. The difference between northern Canada and the western United States in determining the form of the climax vegetation is generally due to the reduced level of precipitation in the latter area. Precipitation levels in both the Elliot Lake and northern Saskatchewan regions are not a primary restrictive factor in forest development.

The possibility of a forest cover considerably increases the advantages and potential for vegetation cover as a primary cover type in Canada. Greater emphasis should be given to this cover form in developing long term stable covers than is given to it in the U.S.A.

The technology of direct vegetation for Canadian conditions is reviewed in sections III.2.7 and IV.1.2 of the Technical Memoranda.

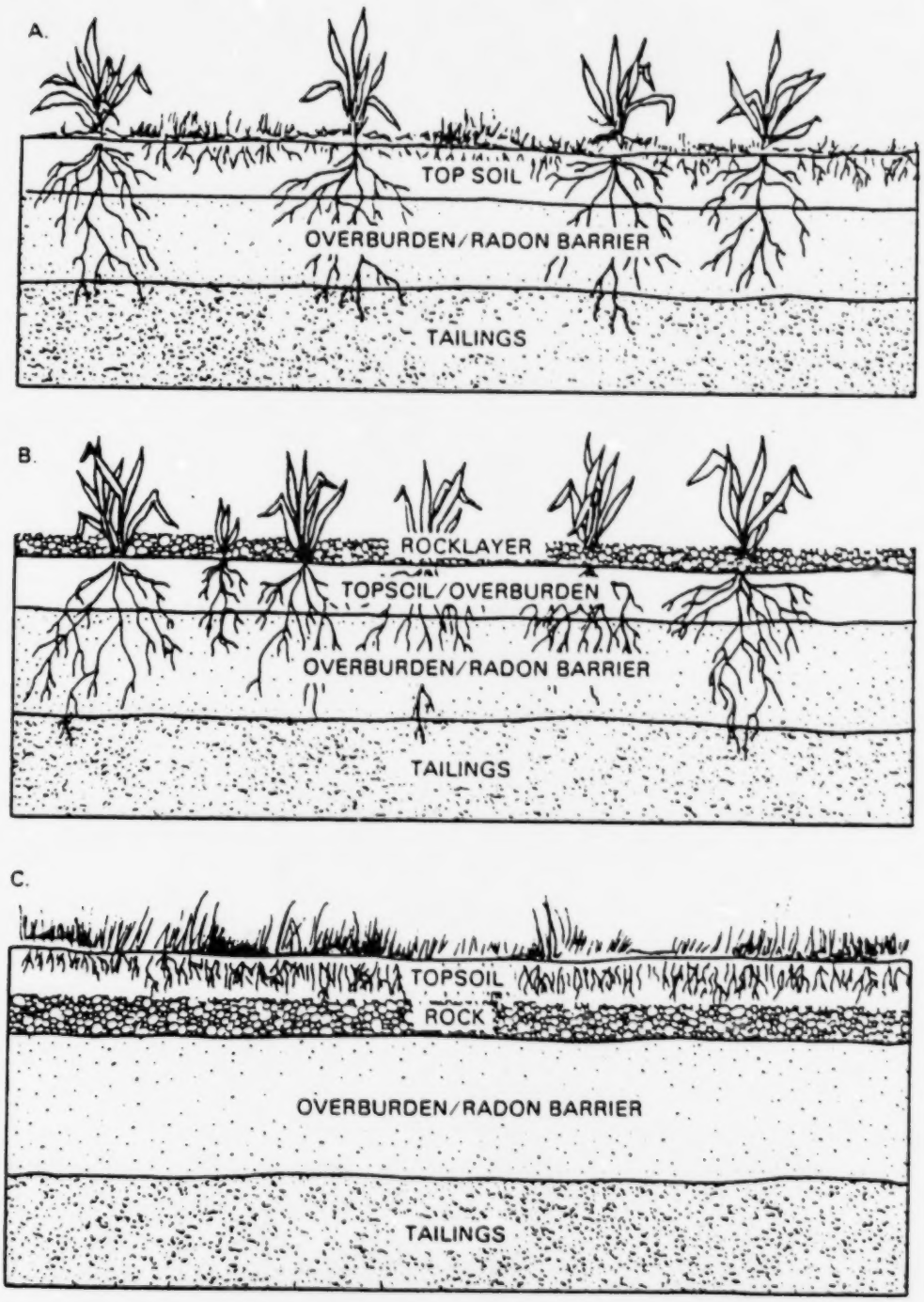
Procedures for designing reclamation programs have been discussed by numerous authors (e.g., Downs and Stocks, 1977; Marshall, 1982; Watkin and Watkin, 1982). In general, three major design approaches can be considered.

1. Direct seeding of tailings with agronomic seed mixtures following addition of a soil amendment (e.g., agricultural limestone, organic waste, acidifying chemicals) and fertilizer.

2. Seeding and/or planting of native or indigenous species having a high tolerance to adverse conditions identified as present on the tailings.

3. Isolation of adverse tailings conditions by covering with one or more capping materials (e.g., topsoil, overburden, rock waste, bentonite) and seeding thereon with native, indigenous or agronomic species.

In practice, the three approaches are not mutually exclusive and two or even three approaches may be applied at a particular site depending upon



BASIC COVER DESIGNS USING VEGETATION

FIGURE 4

the outcome of initial site investigations and subsequent reclamation plan development. No one method should be advocated to the exclusion of the others. Successful reclamation is dependent upon a flexible and open minded approach in devising reclamation programs.

The approach to establishing a forest climax cover on the tailings area has been one of designing abandonment practices which will provide for immediate control of erosion processes by establishing an herbaceous vegetation cover, and in which the process of material plant succession will lead to the development of a forest cover thereon. The pattern of vegetation establishment will be as follows:

(a) Initial type composed of legumes, grasses and other herbaceous species to provide rapid surface erosion control. Where proper species selection and establishment practices have been carried out, such vegetation cover should persist for at least 50 years. Seeded or planted species may be agricultural species or species selected from natural plant communities of the region. Vegetation cover established with these species should not be of a type that precludes invasion and colonization by other species.

(b) Secondary type composed of regional shrub and tree species which colonize the initial vegetation type. In some instances shrub and tree species may be deliberately seeded or planted to hasten the development of a forest type cover. This is not considered a potential practice on uranium tailings sites in Canada.

The natural colonization of herbaceous seeded tailings areas by shrubs and trees is considered extremely important. Colonization indicates that natural, self-sustaining and self-perpetuating processes are occurring in plant and "soil" communities leading to the development of a stable vegetative community. Although the floristic community developing may not be entirely reflective of offsite adjacent communities, it will exhibit similar characteristics for controlling erosion and wildlife development.

2.2.2 Loss of Vegetation Cover

The most common causes of loss or failure of a vegetation cover on tailings or tailings covered surfaces is inadequate site preparation. That may take many forms:

i) Failure to design final surfaces to prevent erosion from spring melt or heavy summer storms, persistent ponding of water, too steep and/or too long slopes, irregular final surface which enhances gully erosion, compaction of overburden covers during placement, reduced permeability from multi-layer overburden covers and use of overburden materials that exhibit poor plant growth support characteristics.

ii) Insufficient addition of soil amendments to tailings acidity or alkalinity (salinity) prior to vegetation establishment (Section IV.1.6.1).

iii) Inadequate determination of plant fertilizer requirements causing low nutrient status conditions by too little fertilizer application (Section IV.1.2).

iv) Selection of plant species for the initial vegetation cover which are not adapted to the physical and chemical conditions of the site. This applies both to the selection of agronomic and native species (Section III.2.7).

v) Unsatisfactory seedbed preparation by reclamation contractors followed by additional poor quality materials application (shortages, omission of correct legume innoculation procedures, unsuitable matches and/or soil chemical stabilizers).

vi) Seeding at the wrong time of year, particularly too late so that establishing vegetation has not reached a growth stage capable of surviving the winter.

There are numerous other causes of vegetation loss, some of which can be controlled to a certain degree.

i) Destruction of vegetation by recreational vehicles (dirt bikes and/or 4-wheel drive vehicles). Major erosion problems can be caused by the activities of these vehicles.

ii) Catastrophic events such as flooding and erosion from severe storms (100 year event) and forest fires (Section IV.2).

iii) Insect and/or plant disease epidemics.

(iv) The failure of chemical control procedures over a period of time, i.e., onset of re-oxidation of iron sulphides, breakdown of impermeable barriers leading to upward migration of acidity and/or salts, leading to contamination of the soil environment (Section IV.1.6.1 and 4).

2.2.3 Vegetation Stability at the Generic Sites

Difficulty has been experienced with the establishment of stable direct revegetation of tailings from low/medium grade ores in both Saskatchewan (represented by the generic Wet Tailings Site) and Ontario (refer section V.1.2). Because of their acid generating potential, sulphide tailings (typical of Elliot Lake) pose a potentially greater problem. The placement of a pyrite free tailings layer on top of the pyrite tailings (refer section V.1.2.1.1) should enable revegetation leading to a forest climax to be achieved. Research is needed to establish what upward migration of salts will occur. Current field observations in Elliot Lake (Denison, personal communication) suggests that with the excess precipitation in the region there is little or no upward salt migration. Where upward salt migration does occur, it may be necessary to design and install stable salt migration barriers.

Tree cover vegetation could be established on a thin soil cover (600 mm) but the stability of this vegetation will depend on preventing upward migration of salts and acidity.

Should the tailings from the nickel/arsenic ores (represented by the Semi-Dry Tailings Site) be phytotoxic then forest vegetation may be impossible on thin covers and thick covers would have to be employed.

Provided appropriate cover construction and placement techniques are used, forest type covers could be established on thick covers on all tailings types. Adequate precautions are needed to prevent salt migration, flooding, etc.

2.3 WATER EROSION

Water erosion is one of the most likely mechanisms of long term disruption of a tailings cover. Mechanisms of interest include:

2.3.1 Flood Erosion

A substantial proportion of total erosion occurs during extreme precipitation and flood events. The methodology for flood estimation is reviewed in section III.2.1 of Technical Memorandum III, and the determination of river erosion potential and its impacts on tailings impoundments in III.2.2.

None of the generic sites are located in positions threatened by river flood erosion.

The erosion of drainage channels, spillways and diversion structures, during flood events, is reviewed in section IV.5.2 where design methodologies are identified. Failure of these structures would lead indirectly to cover failure. In addition to flood induced scour failures, these structures could also fail as a result of sedimentation, ice and debris blockage which would result in flooding of the cover, and potentially cover scour or vegetation kill. The likelihood of such failures is evaluated in a separate study undertaken for the NUT Program (Steffen, Robertson & Kirsten, 1986).

2.3.2 Sheet and Rill Erosion

The available technology for the estimation of sheet and rill erosion is reviewed in section III.2.3. Methods for the design of erosion resistant covers are described in III.2.5, discussed and evaluated in IV.3.1 and applied to the generic sites and selected covers in V.1.3.

The most suitable methods for predicting sheet and rill erosion are:

a) Unified Soil Loss Equation (USLE) (Wischmeier and Smith 1978)

b) Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975)

The USLE estimates gross soil losses for all water erosion from an area. The MUSLE can be used to determine soil loss from single storm events which

can be large for large storm events. Estimates of soil loss are based on a number of factors which have been developed for various regions of the USA. These factors are not necessarily representative of Canadian conditions but must be used in the absence of any factors developed specifically for Canada. It is recommended that factors appropriate to Canadian conditions be developed to more realistically determine long term erosion potential at the location of the tailings sites.

Computer codes such as WASHMO and WASHED (Ward et al, 1981) can be used for MUSLE calculations.

Using these methods, the erosion release rates over a 1000 year period were estimated for each of the generic tailings sites and the results are summarized in Tables 3, 4 and 5.

From the tabulated results the following conclusions can be drawn:

- Bare tailings are subject to significant (2 mm/year) sheet erosion rates and would result in unacceptable release rates.
- Good grass (or forest) cover reduces sheet erosion to insignificant quantities.
- Thin silty soil or till covers would erode away entirely in a 1000 year period unless protected by a vegetative cover. However even a sparse grass cover will effectively stabilize the till.
- Sandy, coarse tills and/or glaciofluvial gravels would be stable.
- Waste rock covers would be stable.

From the above evaluation it is apparent that sheet and rill erosion will be responsible for instability and unacceptable release rates for the following cover alternatives.

- bare tailings with little or no sparse vegetation cover
- thin (0.6 m) silty soil or till covers without vegetation

The remaining alternative covers are considered stable in the long term.

Water cover at the Elliot Lake site would prevent sheet and rill erosion.

2.3.3 Gully Erosion

The only method of gully erosion estimation which may be applicable to stability analyses for covers is the method proposed by Falk et al (1985). The method of gully erosion prediction is described in III.2.4 and its application to Canadian conditions evaluated in IV.3.1. Limitations of this method are:

- developed from limited American data
- not developed for uranium tailings data
- does not account for variations in vegetation cover

TABLE 3

ESTIMATED SHEET AND RILL EROSION FOR TYPICAL
ELLIOT LAKE TAILINGS SITE
OVER A 1000 YEAR PERIOD

COVER TYPE	EROSION DETERMINED BY USLE (m)	EROSION DETERMINED BY MUSLE (m)	TOTAL EROSION (m)
1. Tailings cover			
a) bare tailings	2.0	0.3	2.3
b) sparse grass	0.2	0.03	0.23
c) good grass	insignificant	insignificant	insignificant
2. Till cover			
a) bare material	0.6	0.1	0.7
b) sparse grass	0.1	0.01	0.11
c) good grass	insignificant	insignificant	insignificant
3. Waste rock			
a) bare material	0.1	insignificant	0.1
b) sparse grass	insignificant	insignificant	insignificant

The factors used for erosion estimation are summarized in TMV-V.1.3.1

TABLE 4

ESTIMATED SHEET AND RILL EROSION FOR TYPICAL
SASKATCHEWAN WET TAILINGS SITE
OVER A 1000 YEAR PERIOD

COVER TYPE	EROSION DETERMINED BY USLE (m)	EROSION DETERMINED BY MUSLE (m)	TOTAL EROSION (m)
1. Silty till cover			
a) bare material	0.6	0.2	0.8
b) sparse grass	0.06	0.02	0.08
c) good grass	insignificant	insignificant	insignificant
2. Sandy till cover			
a) bare material	0.3	0.1	0.4
b) sparse grass	0.03	0.01	0.04
c) good grass	insignificant	insignificant	insignificant
3. Waste rock cover			
a) bare material	0.1	0.04	0.14
b) sparse grass	insignificant	insignificant	insignificant

Note: - Bare tailings erosion rates are assumed to be similar to those for the Elliot Lake site.
- Factors used for erosion estimation are given in TMV-V.1.3.2.

TABLE 5

ESTIMATED SHEET AND RILL EROSION FOR TYPICAL
SASKATCHEWAN SEMI-DRY TAILINGS SITE
OVER A 1000 YEAR PERIOD

COVER TYPE	EROSION DETERMINED BY USLE (m)	EROSION DETERMINED BY MUSLE (m)	TOTAL EROSION (m)
1. Tailings cover			
a) bare tailings	0.8	0.5	1.3
b) sparse grass	0.08	0.05	0.13
c) good grass	insignificant	insignificant	insignificant
2. Sandy till cover			
a) bare material	0.2	0.1	0.3
b) sparse grass	0.01	0.01	0.02
c) good grass	insignificant	insignificant	insignificant
3. Waste rock cover			
a) bare material	0.06	0.03	0.09
b) sparse grass	insignificant	insignificant	insignificant

Factors used for erosion estimation are given in TMV-V.1.3.3.

TABLE 6

ESTIMATED DEPTH OF GULLY EROSION ON
COVERS FOR GENERIC IMPOUNDMENT SITES
FOR A 200 YEAR PERIOD

SITE	COVER MATERIAL	GULLY INCISION DEPTH (m)
1. Elliot Lake Site	tailings	4
	till	4
	waste rock	1
2. Saskatchewan Wet Tailings Site	silty till	6
	sandy till	4
	waste rock	3*
3. Saskatchewan Semi-Dry Tailings Site	tailings	6*
	silty till	4*
	waste rock	2*

* Parameters fall outside limits of Falk equations. Estimates based on original equations (see V.1.3).

- is based on data from impoundments less than 35 years old and is considered invalid for periods greater than 200 years

Using this method the depth of gully incision was estimated (Refer TM V.1.3) for the various cover materials on the various generic impoundments as summarized in Table 6.

The depth of incision is substantially dependent on the tributary drainage area, as well as the average grain size of the cover material. Control of gully erosion can therefore be achieved by constructing contoured drainage ditches on the impoundment cover, thereby reducing the maximum size of the tributary drainage areas. Such ditches would have to be protected from channel erosion by placing riprap.

The estimated gully depths are large and may be expected to be even larger if a 1000 to 2000 year time frame is considered. Field experience of gullying is that deep gully formation can be anticipated in less than 200 years in both the tailings and till type materials. The authors question the accuracy, but not the prediction of deep gullying, of this method. It is considered that the prediction method does not adequately reflect the gully resistant effects of heavy vegetation cover, particularly forest cover, or of coarse waste rock or riprap cover materials.

From the results of this evaluation it is concluded that:

o deep gully erosion can be anticipated in all the tailings and till covers.

o a thin (600 mm) waste rock cover may resist gully erosion for a period but once breached will have little effect.

o current gully estimating technology is inadequate to determine the gully resistance from forest cover or coarse waste rock. It is anticipated that these cover types would demonstrate significantly lower gully potential than is predicted by the method of Falk et al (1985).

o contour drainage, using riprap lined ditches to reduce gully tributary areas, is an effective method for gully erosion control

2.4 WIND EROSION

Wind erosion is observed to be a major release mechanism on many of the existing tailings impoundments (refer Table 1). The control of this mechanism for the long term depends on the successful establishment and maintenance of a wind erosion resistant cover, such as vegetation, waste rock or surface crusting.

The methods of determining the wind erosion potential and release rates of a particular cover type is reviewed in sections III.3.2 to 3. The application of this technology to Canadian tailings deposits is reviewed in IV.3.2 and estimates of release rates are made for the three generic sites in V.1.4. The results of these estimates are summarized in Table 7.

TABLE 7

SUMMARY OF WIND EROSION RELEASE RATE ESTIMATES FOR VARIOUS COVER MATERIALS AT GENERIC CANADIAN SITES OVER 1000 YEARS

SITE AND COVER	WIND EROSION DEPTH (m)
1. Elliot Lake Site	
(a) tailings with good grass cover	5-10
(b) till with good grass cover	3-6*
(c) tailings or till with tree cover	small
2. Saskatchewan Wet Tailings Site	
(a) silty till with good grass cover	1-4*
(b) sandy till with good grass cover	2-8*
(c) till with tree cover	small
(d) waste rock cover	insignificant
3. Saskatchewan Semi-Dry Tailings Site	
(a) tailings with good grass cover	10-30
(b) sandy till with good grass cover	3-10*
(c) tailings or till with tree cover	small
(d) waste rock cover	insignificant

*does not take into account long term coarse particle armouring during deflation.

With bare tailings, large release rates are anticipated at all inactive tailings sites. This is consistent with observations at Gunnar where wind transported tailings of up to 1 m depth have been reported around the tailings perimeter (Kalin, 1983). With the establishment of good grass cover, the estimated rate of wind erosion is still sufficiently high that both thin and thick tailings or till covers may be eroded away entirely in 1000 years. The establishment of tree cover is required to stabilize tailings or till covers. Wind erosion from waste rock covers would be insignificant.

The analysis does not allow for the effect over a long time of coarse particle accumulation that occurs during wind deflation. This effect is expected to be very significant where the tills contain significant percentages of coarse particles. Since most of the tills at the generic sites contain a significant proportion of gravel sized particles (refer Figures II.3.4-2 and 3, and II.4.2-2), the amount of deflation required to produce an armoured surface can be quite small (a few tens of centimeters). The selection of tills with high gravel contents would be an effective wind erosion protection cover.

Based on the results in Table 7 and the above observations it is concluded that:

- o unacceptably high wind erosion rates occur on tailings and soil covers (without gravel) unless a tree cover is established. Loss of tree cover (due to forest fires) could result in unacceptably high rates of wind erosion releases.

- o till, with a substantial gravel percentage, and rock waste will form effective wind erosion layers when placed in thin (600 mm) cover layers.

While wind cannot cause wind erosion of water covered tailings, it does produce wave action. Where a shallow water cover is employed (600 mm) the seasonal fluctuations in water depth combined with wave action may result in disturbance and suspension of tailings fines. Such fines may be deposited on the beach edges from where it is readily released to the environment. While release rates have not been estimated it is concluded that shallow water cover could result in the release of unacceptable quantities of tailings.

With deep water cover (3 m) the effect of wave action is limited to the beach zones. If tailings erosion in these areas are prevented (by rock waste cover for example) releases would be small and probably insignificant.

2.5 FROST ACTION

Frost action of three types are of concern.

(i) Seasonal frost may result in frost pumping of pore fluid to the surface and may cause a decrease in the density and an increase in the permeability of infiltration barrier layers or caps.

(ii) Permafrost aggradation may result in a heave of the tailings cover, disrupting any barrier layers or drainage, elevating tailings and preventing tree cover development. Such aggradation is reported at Gunnar.

(iii) Inclusion of masses of low density frozen tailings in the tailings mass, during placement, followed by thawing and consolidation may result in settlement of the cover, disrupting barrier layers or drainage.

Frost action requires 3 essential elements.

a) freezing temperatures
b) a frost susceptible soil
c) a free supply of water

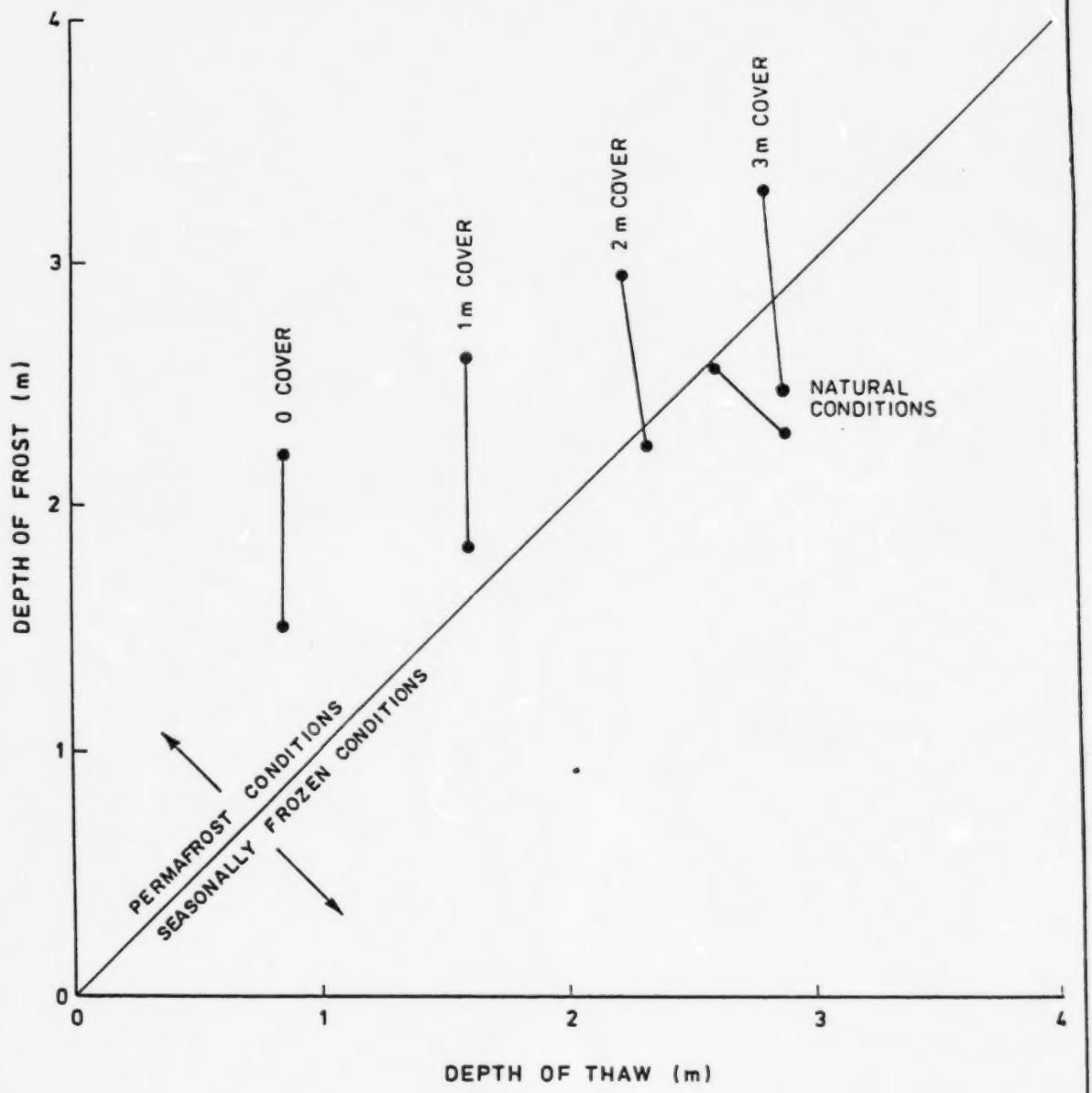
The Saskatchewan uranium producing areas are in northern latitudes where severe winters are common. The conditions are sufficiently severe for discontinuous permafrost to occur which becomes more prevalent in the more northerly latitudes. The Ontario uranium producing areas are more moderate in climate, permafrost has not been encountered in the tailings, however freezing conditions are common. The approximate freezing indices are 3200, 2700 and 1100 degree days Celsius at Uranium City, Key Lake and Elliot Lake respectively.

The tailings are predominantly composed of silt and very fine sand sized particles and are frost susceptible. The uranium producing areas are all north of the sedimentary basin. Thus, fine grained clay soil is not available for embankment construction and frost susceptible silt or silty sand is the least permeable soil available. Therefore, both the tailings themselves and the borrow soil available for embankment and cover construction are generally frost susceptible.

Free water is available within the tailings mass in sufficient quantity for ice accumulation to occur.

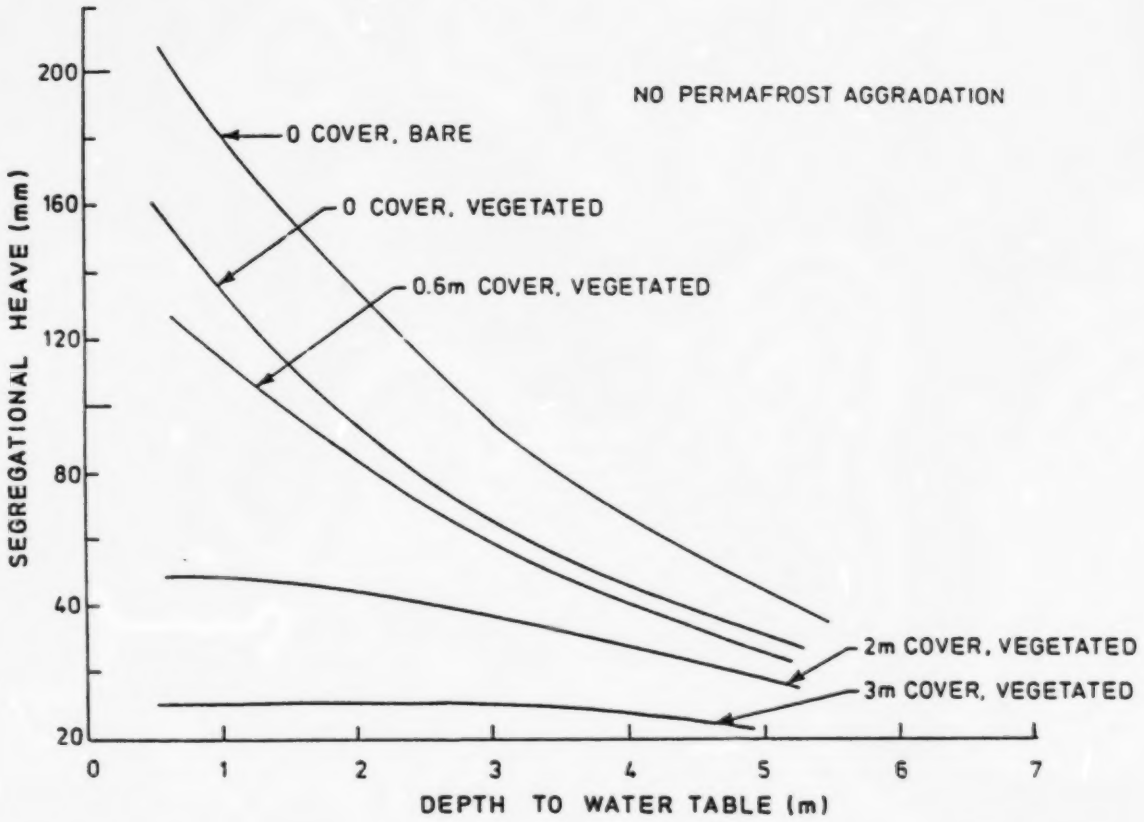
The methodology for the estimation of frost depths and aggradation is reviewed in section III.4.1 and 2. This methodology has been applied to typical conditions for northern Saskatchewan tailings sites and for various cover materials in section IV.3.5.3. The resulting estimates of freezing and thawing depths are given on Figure 5. The area above the diagonal line illustrates conditions favourable for permafrost formation while areas below the line illustrate conditions unfavourable to permafrost formation. In most of the cases analyzed, the seasonal depth of frost was greater than the seasonal depth of thaw, which would result in the development of perennially frozen soil.

Frost penetration is dependent upon the thermal characteristics of the cover material, moisture content, height of the water table and vegetation cover. The effect of vegetation cover and depth to water table on the segregational heave is illustrated for the Saskatchewan wet tailings site in Figure 6.



COMPARISON OF FREEZING AND THAWING DEPTHS FOR TYPICAL SASKATCHEWAN CONDITIONS

FIGURE 5



POTENTIAL TAILINGS FROST HEAVE, W.T. SITE
NORTHERN SASKATCHEWAN

FIGURE 6

Estimates have been made of freezing and thawing depths (and the ratio of these) as well as the potential fluid release by pumping, for each of the generic Saskatchewan sites (refer V.1.6.3), and each of the alternative cover types. The results are summarized on Tables 8 to 11.

From these tables it is concluded that:

- o a vegetated cover layer of at least 2 m thickness is probably required to prevent permafrost development in the tailings
- o fluid pumping of very substantial quantities of tailings pore fluids can be expected if depths of cover are less than 2 m. For unzoned covers the released fluid must move to the surface. For zoned covers, the fluid can be intercepted by the drainage zone and run off to a discharge point.

Frost action on the cover can initiate freeze cracking of infiltration barriers. The effects of freeze cracking increase with the plasticity of the soil. No naturally occurring materials with sufficient plasticity for concern are available. However, bentonite additives for infiltration control must be used with caution in a freeze-thaw environment. Control over the degree of disturbance is possible by placing the infiltration barrier at the lower part of the cover where the temperature differences are moderated.

Where deep water cover (3 m) is installed, frost action is prevented. If shallow water cover is used (600 mm) then the frost depth considerably exceeds the cover depth and the frost induced releases discussed above apply.

An additional frost release is associated with shallow water cover. The freezing depth extends down into the tailings. During thawing these frozen tailings are rafted upwards and may be carried by wind or ice rafting up the beaches. Release rates due to this mechanism have not been estimated but are considered to be potentially large over the long term.

2.6 BIOLOGICAL PENETRATION

2.6.1 Root Penetration

Root growth is governed by numerous individual factors and by various interactions between those factors (see Section III.5.1).

It is known, from visual observations primarily, that plant roots growing directly in tailings will grow to the interface between the treated depth of tailings (i.e., limed, fertilized) and the untreated underlying tailings zone. Root growth then occurs laterally along the interface, not into the untreated tailings. The tendency of roots to enter drains is well documented. In the case of tailings covers constructed with internal rock drains, blockage of these drains and subsequent flooding of the tailings cover (killing tree growth) or erosion may be the cause of cover failure.

Most infiltration barrier layers will be constructed of glacial till materials or bentonite modified sands. Depending upon environmental

TABLE 8

PREDICTED FREEZING-THAWING DEPTH,
WET TAILINGS SITE, SASKATCHEWAN

CASE	FREEZING DEPTH (m)	THAWING DEPTH (m)	RATIO
No cover, bare	2.2	1.1	.50
No cover, vegetated	1.6	1.15	.72
0.6 m cover, vegetated	1.9	1.6	.84
2 m cover, vegetated	2.6	2.7	1.04
3 m cover, vegetated	3.1	3.5	1.12

TABLE 9

PREDICTED FREEZING-THAWING DEPTH,
SEMI-DRY TAILINGS SITE, SASKATCHEWAN

CASE	FREEZING DEPTH (m)	THAWING DEPTH (m)	RATIO
No cover, bare	2.0	.85	.42
No cover, vegetated	1.48	.85	.57
0.6 m cover, vegetated	1.75	1.3	.74
2 m cover, vegetated	2.5	2.4	.96
3 m cover, vegetated	3.1	3.2	1.03

TABLE 10

POTENTIAL FLUID RELEASE FROM FROST "PUMPING",
WET TAILINGS SITE, SASKATCHEWAN

	MAY	JUNE	JULY	AUG.	SEPT.	OCT.
Mean Temperature °C	4.7	11.8	15.5	13.8	6.7	0.61
Potential Evapotranspiration (mm)	4.9	105	127	103	48	0
Precipitation (mm)	27	51	64	56	51	33
Net potential evaporation (mm)	22	54	63	47	-3	-33
Fluid Released by thaw:						
No cover, bare (mm)	63	37	28	24	20	18
No cover, vegetated (mm)	45	27	22	18	15	14
0.6 m cover, vegetated (mm)	32	26	20	16	15	13
2 m cover, vegetated (mm)	0	0	11	13	11	10
3 m cover, vegetated (mm)	0	0	0	0	0	8

NOTE: Water table at 1 m depth

TABLE 11

POTENTIAL FLUID RELEASE FROM FROST "PUMPING",
SEMI-DRY TAILINGS SITE, SASKATCHEWAN

	MAY	JUNE	JULY	AUG.	SEPT.	OCT.
Mean Temperature °C	6.1	12.9	15.6	14.4	7.9	1.6
Potential Evapotranspiration (mm)	57	109	125	104	53	12
Precipitation (mm)	26	51	79	61	57	30
Net potential evaporation (mm)	31	58	46	43	-4	-18
Fluid Released by thaw:						
No cover, bare (mm)	28	17	15	13	12	11
No cover, vegetated (mm)	20	12	10	8	8	8
0.6 m cover, vegetated (mm)	14	12	10	9	8	8
2 m cover, vegetated (mm)	0	0	6	8	8	8
3 m cover, vegetated (mm)	0	0	0	0	0	4

NOTE: Water table at 3 m depth

conditions existing at the interface of those controlling layers and the upper material layer (see Section III.5.1) root penetration and proliferation leading to structural failure could occur. Once failure has occurred, an increase in oxygen and water migration may occur, resulting in movement of acidity or salts or to the oxidation of pyrite in previously inactive tailings.

The impact on releases is considered to be small for the low sulphide tailings from low grade deposits in Saskatchewan. For the sulphide rich Elliot Lake tailings, the impact may become significant. For the nickel/arsenic, sulphide tailings from high grade ore deposits in Saskatchewan, the effect on releases may be considerable as a result of increased radon emanation, infiltration and possibly salt migration leading to loss of vegetative cover and erosion.

Root action is a secondary mechanism which may contribute to the failure of a cover by other mechanisms (erosion, infiltration, etc.) The current understanding of the potential of biological penetration by root action was insufficient to enable release rate estimates to be made within the scope of this study. However, the potential for increased releases by this mechanism is considered to be relatively minor.

2.6.2 Burrowing Activity

A slow but long term transport and release of uranium tailings by the activities of burrowing animals has been reported by researchers in the western United States. The extrapolation of such findings to the regions of Canadian uranium mining activity should be done with caution. Because of inherent differences in climate, vegetation type (grassland versus forest) and accompanying differences in biota type and population, burrowing activities would not be considered a major form of release of tailings. The releases are considered to be low at the low/medium grade uranium mines in Canada. However, even a low level of burrowing activity could be a source of concern and environmental impact where tailings are highly radioactive and toxic, where even small releases would be considered significant.

Insufficient data exists on the extent of burrowing intrusion in Canada to enable realistic estimates of tailings release rates. It is expected to be very small for all thick covers (3 m) and insignificant where a biobarrier is installed (1 m of dense coarse rock waste).

It is presumed that the prevention of intrusion by man will be assured by institutional or other means.

2.7 WEATHERING AND SALT MIGRATION

2.7.1 Weathering

Cover materials formed from the soils excavated from the vicinity of the tailings impoundment are expected to be geochemically stable and undergo little change due to weathering, in the 1000 to 2000 year period of interest. The same conclusion applies to riprap materials derived from coarse till deposits.

Waste rock from the mine or riprap quarried specially for the cover may be geochemically less stable and their long term stability should be evaluated. Methodologies for the assessment of the durability of such waste rock/riprap cover materials has been reviewed in section III.2.10.

Durable sandstone and quartzite rock waste and quarry material can be obtained at the generic Saskatchewan and Ontario sites. Thus, weathering of cover materials is not considered a potential cause of instability and releases for any of the cover types evaluated.

2.7.2 Salt Migration

(a) Leaching

The geochemical processes for the leaching of uranium tailings and solute transfer have been identified in section III.6.7. Geochemical effects and pore water changes have been evaluated and projections made of the change of pore water chemistry with time in IV.3.4. An evolution of pore water geochemistry at the Elliot Lake site is anticipated, Clifton Associates (1986), as follows:

0-20 years (or impoundment operational life)	-	process controlled stage
20-~200 years	-	sulphide oxidation stage
~150-~600 years	-	resolution stage
~500-~1000 + years	-	long term leaching stage

Data derived for the behaviour of the Elliot Lake tailings reflect periods for tailings deposition and subsequent inactivity of the order of 20 to 30 years. This establishes an approximate beginning for the second stage of pore water evolution. Determining the approximate duration of this stage is problematic. Dubrovsky et al (1985) note a rate of migration downwards of the acidic zone in pyrite tailings of 0.2-2 m/yr. This rate of downward advance is slower than the infiltration rate/seepage rate, due to the retardation of the acidic zone, through neutralization, during transport downwards. There is a capacity for acid generation until all the pyrite is oxidized, after which the tailings would be "flushed" with relatively low TDS, rainfall or snowmelt infiltration. Given the present rate of infiltration, acid generation resulting in a high TDS, high sulphate and iron seepage water composition will continue for many decades.

Based on the above geochemical sequence, an estimate of the pore water quality for the various representative Canadian uranium tailings deposits was made as is summarized on Table 12.

The time rate of sulphide oxidation will be influenced by the nature of the cover material placed on it. Inclusion in the cover of infiltration barrier layers will reduce both the rate of infiltration and leaching and the entry of oxygen for oxidation. The pore water quality may not improve

TABLE 12

PORE WATER QUALITY CHANGES WITH TIME

	Process Controlled Stage All Tailings	Sulphide Oxidation Stage Elliot Lake	Resolution Stage ** Elliot Lake Type Tailings 1	Resolution Stage ** Key Lake and Rabbit Lake Type Tailings 2	Long Term Infiltration Phase All Tailings
pH	7-10	2	3.5	7.5	5
TDS	2,500-8000	30,000	2,500	2,500	100
Ca	500-800	500	400	400	20
SO_4	1,500-5000	20,000	1,800	1,200	10
NH_3	<10-350	<10	<10	<10	<1
Na	<50-600	100	20	20	10
Cl	<50-700	200	20	20	10
Fe	<1	10,000.*	20	5	<1
Mg	1-900	200	50	<5	10
As	.1-2	1	<1	<1	<0.1
Ra_{226}	<20-50	<5	<20	<10	10
Al	<1-3	20	20	<5	5
Si	<5-20	20	20	<5	5
Ni	<.1-1	1	<.1	<.1-1	<1

pH expressed in standard units; all other parameters in mg/L.

* If oxidizing ore is pyrite or iron-bearing sulphide

** May be accompanied by alteration of jarosite, in iron-bearing tailings

but the seepage quantity will reduce and the period of sulphide oxidation will increase. Inclusion of a suction break layer under the infiltration barrier would result in reduced infiltration (hence a drop in the water table) and optimum conditions for oxidation. Thus the cover layers that minimize infiltration may result in the worst seepage water quality.

Several lysimeter type studies (see section IV.1.6) have been reported where vegetative cover has been established on acidic tailings from various metal sources. Generally, the conclusion has been drawn that a vegetative cover does not reduce pyrite oxidation or acid seepage.

Placement of a water cover over the generic Elliot Lake site would inhibit the oxidation of the pyritic tailings. Thus, while the seepage rates would be considerably increased, the quality of seepage waters will improve most rapidly.

(b) Upward Salt Migration

The potential for upward salt migration is reviewed in section III.6.8.

The importance of upward salt migration in tailings is very difficult to quantify from a reclamation - revegetation viewpoint in the Elliot Lake and northern Saskatchewan mining areas. Practical reclamation experience from several mining areas (Noranda, P.Q., Red Lake, Ontario, Bathurst, N.B.) strongly suggests that upward salt migration is solely a phenomenon associated with non-revegetated tailings areas. Where tailings have been direct seeded, the phenomenon has not been recorded as being problematic. Extreme variability in tailings chemical properties is, however, an established factor. It would, therefore, be improper to unequivocally dismiss upward salt migration as a potential reclamation problem in future reclamation programs whether in the Elliot Lake, Northern Saskatchewan or other regions of Canada. Denison Mines (personal communication) indicate that no upward salt migration has been observed, to date, in the Elliot Lake region, possibly because of the net precipitation in the area.

Conflicting reports (most as personal communications) have been received by the authors as to the occurrences and intensity of upward salt migration into overburdens placed over tailings. Since upward salt migration will be governed by type and thickness of overburden, and by precipitation and temperature patterns in any one year, the variability in reporting is not unexpected.

In the absence of reliable information to the contrary it is assumed that upward salt migration has a likelihood of occurrence for all covers where a well developed vegetation cover is absent.

It is considered that there is only a low likelihood of upward salt migration into the deep cover layers and a negligible risk where a suction breaker or barrier is included.

Where a water cover is installed, the only mechanism for upward salt migration would be molecular diffusion, and negligible release rates would occur.

Estimates of release rates due to salt migration were not made in this study. Consequential releases as a result of wind or water erosion following vegetation kill caused by salt migration is potentially the major release mechanism.

2.8 PHYSICAL INSTABILITY

Dimensional changes in the foundation, which supports the cover, or of the cover layers can result in cracking of the cover (refer to section IV.3.5.1). Such cracking may result in the same causes of secondary release discussed in section 2.6. For similar reasons it is considered that cover failure by these mechanisms would be insignificant in the cases of all cover types for the tailings from the low/medium grade uranium ores of both Ontario and Saskatchewan. It may be significant in the case of the Saskatchewan nickel/arsenic, sulphide ores. Consequential release rates would be small and have not been estimated in this study.

Differential settlements in the tailings may result from a number of causes as discussed in IV.3.5.1. Estimates were made of the potential total settlements of the generic tailings sites in Saskatchewan (refer sections II.3.5 and II.4.5). Total settlements of 2 to 3 m were calculated with consolidation periods of 13 and 30 years for the wet and semi-dry sites respectively. Assuming that differential settlements were 50% of total settlements, and that it can occur within 50 m, the slope change would be 2% to 3%. This is large enough to cause ponding on all the proposed covers and an associated loss of vegetation cover. Loss of vegetation cover will result in the wind erosion release rates estimated in section 2.4.

2.9 INFILTRATION

While infiltration does not itself represent a release mechanism, it substantially controls the release mechanism of seepage. In the long term all water infiltrating through the cover must emerge as seepage discharge. The long term control of contaminated seepage requires the long term control of infiltration.

Infiltration is controlled by a wide variety of factors including surface drainage conditions, surface texture and permeability, presence and type of vegetation, amount of and distribution of precipitation and evaporation, soil moisture retention characteristics and evapotranspiration. These factors may change with time and at different locations on the same impoundment surface. Analytical methods of determining infiltration, including layered systems are reviewed in section III.6.2 to III.6.4. They are suitable for the estimation of infiltration under ponded water or steady precipitation conditions. These methods do not allow for evapotranspiration losses or variations in precipitation and evaporation on the soil surface.

The estimation of net infiltration is therefore often based on field observation and empirical estimates. In section IV.3.6, some Canadian experience on infiltration is reviewed.

In section III.5.1 the results of the application of some of the modelling techniques to a tailings impoundment in climatic conditions fairly similar

to those at Elliot Lake (performed for a massive sulphide tailings impoundment in northern Wisconsin) are presented. The types of cover materials were similar to those proposed in this study. The results are presented in Table 13. These evaluations may be taken as indicative of similar cover performance at Elliot Lake. Infiltration rates to the tailings below the cover layers (all of which included a 150 mm bentonite modified soil seal layer) ranged from 16 mm in a dry year for covers which included a drainage layer above the seal layer to 112 mm in a very wet year for the cover without a drainage layer. Use of a soil seal layer without a drainage layer above it resulted in saturation of the cover to the surface for a 4 month period which would be detrimental to vegetation. Inclusion of the drainage layer, above the seal layer, eliminated this problem but dry soil moisture conditions resulted for two and five months for normal and dry years respectively. For the 160 ha of the generic Elliot Lake tailings impoundment area, the infiltration range of 16 to 112 mm translates to 256,000 to 180,000 cubic metres per year or 0.8 to 6 litres per second respectively.

Estimates were made of the infiltration rates applicable to the various cover types at the generic Saskatchewan sites in sections IV.3.6, V.1.5 and V.3.4 The results are summarized in Table 14. The following conclusions are reached:

- In the absence of an infiltration barrier layer and vegetation cover, infiltration rates are fairly high. This is reduced significantly by vegetative cover (particularly a forest cover) and increased significantly by a rock waste cover.

- Installation of an infiltration barrier layer without a drain layer above it may result in seasonal saturation of the surface layer resulting in vegetation kill.

- Installation of drainage layer above the infiltration barrier prevents mounding and therefore both infiltration and saturation of the surface (root zone) layer. The long term stability of this drainage layer, subject to root activity, is questionable.

- At the Saskatchewan sites the infiltration rates anticipated with an infiltration barrier (30 mm/year) is only 25% less than that anticipated with forest cover only. At Elliot Lake the effect of an infiltration barrier is considerably greater.

Infiltration rates resulting from the installation of a water cover will depend on the hydraulic gradients that will develop. If the cover is achieved by simply building up the existing embankments at Elliot Lake and then flooding the impoundment, this would result in mounding within the tailings impoundment to the level of the cover surface. This becomes a problem in seepage migration and not infiltration.

2.10 RADON EMANATION

Radon emanation is of considerable concern at the uranium tailings deposits in the U.S.A. As a consequence the analytical and design methodology for covers is well developed and documented in Rodgers et al (1984).

TABLE 13

WATER BALANCE SUMMARY FOR THREE ALTERNATIVE TAILINGS CAP CONSTRUCTION SYSTEMS FOR CONDITIONS SIMILAR TO ELLIOT LAKE SITE

SEASONAL VARIATION	PRECIPITATION (mm)	RUNOFF (mm)	EVAPOTRANSPIRATION* (mm)	VERTICAL PERCOLATION (mm)	HORIZONTAL PERCOLATION (mm)
			SYSTEM 1		
Normal Year	762.8	128.8	594.1	39.6	0
Driest Year	447.8	115.8	360.4	39.6	0
Wettest Year	1014.0	306.3	561.3	112.8	33.6
			SYSTEM 2		
Normal Year	762.8	128.8	564.6	16.0	53.1
Driest Year	447.8	115.8	322.1	16.0	62.0
Wettest Year	1014.0	118.6	560.6	18.8	316.0
			SYSTEM 3		
Normal Year	762.8	128.8	548.4	16.3	67.8
Driest Year	447.8	115.8	305.8	16.0	62.0
Wettest Year	1014.0	118.6	560.6	18.8	316.0

Evapotranspiration includes plant interception estimated as 20 to 30 percent of total precipitation.

System 1: 0.9 m glacial till over 0.15 m bentonite modified seal layer.

System 2: 0.9 m glacial till over 0.2 m coarse drain over 0.15 m bentonite modified seal layer.

System 3: 0.7 m glacial till over 0.2 m coarse drain over 0.15 m bentonite modified seal layer.

TABLE 14

SUMMARY OF ANNUAL AVERAGE INFILTRATION RATES
AND AMOUNTS AT SASKATCHEWAN SITES

	W.T. SITE	S.D. SITE
Precipitation (mm)	400	415
Cover Area (ha)	90	7
Bare Tailings		
Depth of annual infiltration (mm/year)	80	80
Volume of annual infiltration (m^3/year)	72,000	60,000
Waste Rock Cover		
Depth of annual infiltration (mm/year)	160	160
Volume of annual infiltration (m^3/year)	144,000	120,000
Forested Cover		
Depth of annual infiltration (mm/year)	40	40
Volume of annual infiltration (m^3/year)	36,000	30,000
Bentonite Modified Infiltration Barrier		
Depth of annual infiltration (mm/year)	30	30
Volume of annual infiltration (m^3/year)	27,000	22,500

Emanation rates are dependent on the rate of radon generation in the tailings and also the radon diffusion coefficient of the surficial layers of tailings and cover. Radon diffusion rates depend on the presence of open pores in the material through which diffusion is occurring. Moisture in the tailings or soil fill the pore spaces and reduce diffusion. Figure 7 illustrates the effect of soil moisture on the radon diffusion coefficient. Figure 8 illustrates the effects of different cover thicknesses formed from different soil types with different diffusion coefficients.

Comparison of the range of diffusion coefficients in Figure 7 with those in Figure 8 demonstrates the effectiveness of covers with high moisture contents. Because of the climatic differences, substantially higher average moisture contents are observed in the surficial layers of tailings and natural soils at the Canadian deposit sites than is applicable in the U.S.A. Frost action also results in ice blockage of pore spaces for large periods of the year. Thus the radon diffusion coefficient rates of the Canadian tailings are considerably lower. Radon emanation rates measured in Ontario and Saskatchewan are summarized in sections I.5.3 and Tables I.5.A-1 and I.5.B-3.

Data on the diffusion rates at the Saskatchewan tailings deposits from high grade nickel/arsenic, sulphide ores is at this stage very limited.

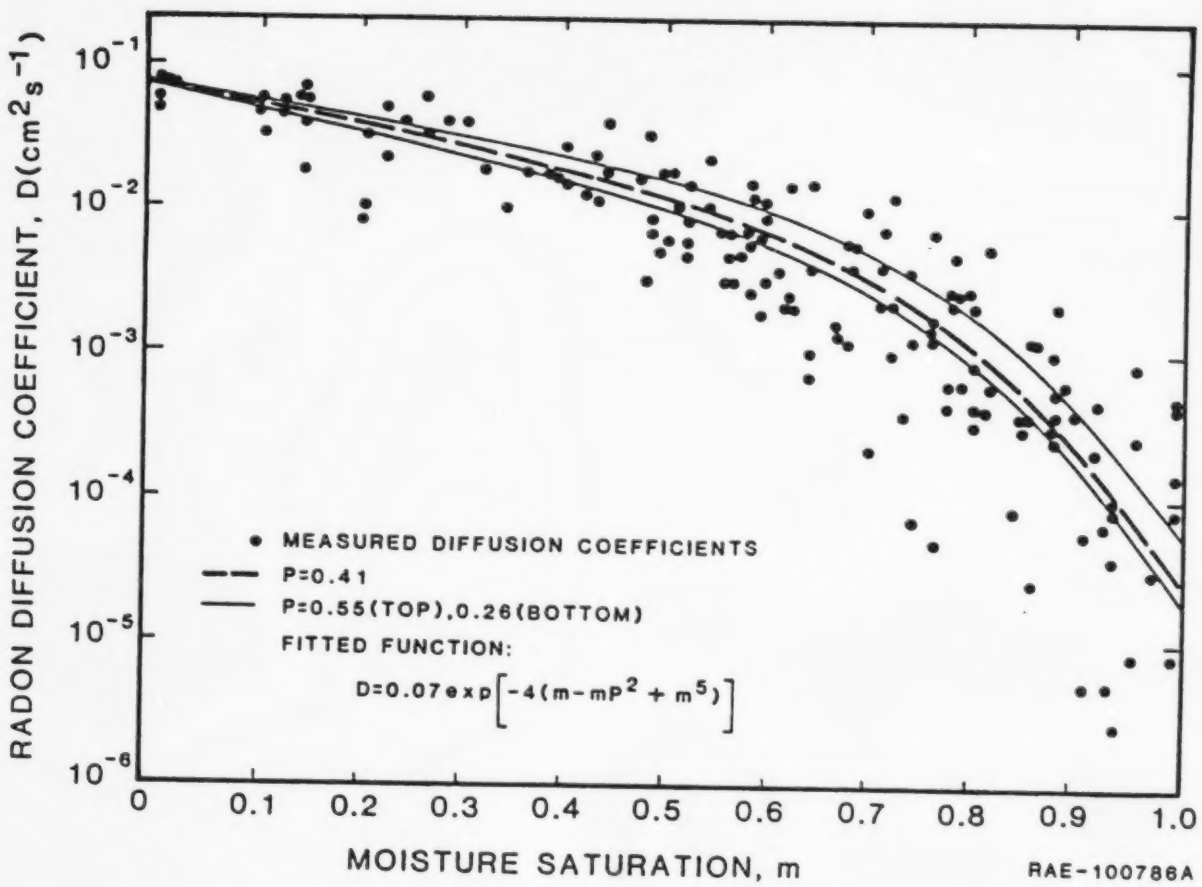
Emanation rates for bare tailings are anticipated to be similar to those currently observed. Vegetation cover alone has been shown (DSMA, 1985) to not inhibit radon emanation. A moderate level of emanation reduction is anticipated for the 600 mm thick rock waste cover. This reduction will depend on the percentage of fines in the waste rock, and the increased average moisture content that will be achieved in the underlying tailings layer. All other soil covers (600 mm till and all thick covers) are expected to reduce radon flux to a small percentage of current surface measurements. Detailed determinations were beyond the scope of this study.

Water covers would effectively prevent nearly all radon emanation.

2.11 COVER COST

Costs for the implementation of various cover types will depend on:

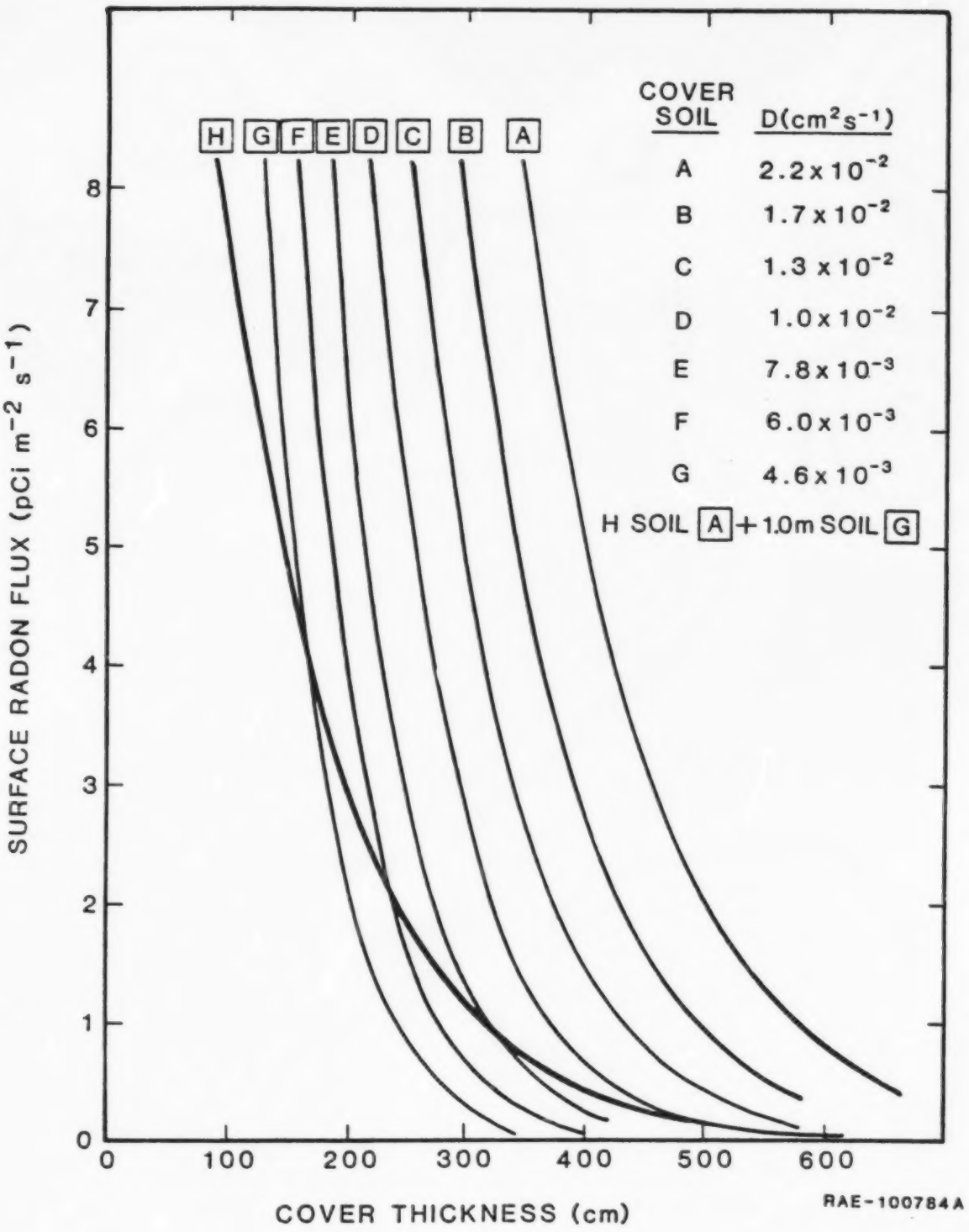
- costing policy of the mine operators, and whether or not the mine has the equipment available to do the reclamation work
- whether or not an outside contractor is used
- accessibility of the site (no road access to some northern Saskatchewan sites)
- proximity of suitable cover materials
- trafficability of the impoundment surface at the time reclamation starts



COMPARISON OF MEASURED RADON DIFFUSION COEFFICIENTS WITH A SIMPLE CORRELATION FUNCTION ASSUMING DIFFERENT POROSITIES

(ROGERS et al, 1984)

FIGURE 7



EFFECT OF SOIL THICKNESS ON SURFACE RADON FLUX
(ROGERS et al, 1984)

FIGURE 8

- volume of surface contouring and ditching required to obtain the desired surface profile and drainage conditions
- whether winter construction will be required to ensure access
- a number of site specific variables

The cost estimates were developed based on a combination of cost figures obtained from mining companies (not necessarily for uranium mines), other comparable contract work and the author's experience. Some cost values such as the cost of achieving pyrite free tailings in Elliot Lake were not available and have been omitted.

The unit rates used are summarized on Table 15. The cost figures shown are considered to be minimum costs which may apply if reclamation work was done by the mine operator using mine equipment and personnel already established on the site; similar to the manner in which reclamation was undertaken at Beaverlodge mine when it shut down. Where an outside contractor and supervision must be brought in to remote locations cost may be 25% to 50% greater than these. Applying these unit rates to the alternative cover types for the generic sites results in the cost estimates per square meter of liner summarized in Table 16. These cost estimates do not allow for major reshaping of the tailings surfaces which may be required on some of the existing abandoned tailings impoundments. These re-shaping costs may be as great or greater than the cost of placing cover materials, if major re-shaping of the impoundment is required. It is assumed that in future, tailings discharge practices will be such that the placement method will result in a final impoundment surface sloped appropriately for reclamation with only minor contouring and drainage preparation.

TABLE 15

SUMMARY OF COVER CONSTRUCTION UNIT COSTS

ACTIVITY	UNIT COST[1]
1. Site Preparation[2]	
(i) good access, minor grading	$0.25/m^2
(ii) poor or winter access, minor grading	$0.50/m^2
(iii) good access, moderate grading	$0.75/m^2
(iv) poor or winter access, moderate grading	$1.00/m^2
2. Vegetation	
(i) non-reactive tailings fertilization and seeding	$0.50/m^2
(ii) reactive tailings	
(a) lower limestone demand and cost	$1.50/m^2
(b) higher limestone demand and cost	$2.50/m^2
3. Waste Rock Cover	
(i) waste rock, < 3 km haul	$2.50/m^3
(ii) blasted rock, < 2 km haul	$4.50/m^3
(iii) extra over (i) and (ii) for winter placement	$1.00/m^3
(iv) extra over (i) and (ii) for haulage	$0.30/m^3/km
4. Soil/Till Cover	
(i) till, < 3 km haul	$2.50/m^3
(ii) extra over (i) for winter placement	$1.00/m^3
(iii) extra over (i) for haulage	$0.30/m^3/km
5. Barrier Layers	
(i) compacted selected rock or soil barrier layers (extra over 3 and 4 above)	$1.00/m^3
(ii) bentonite modified sand	$10.00/m^3

1. Considered to be minimum costs where work is done by established mine personnel and equipment.

2. Does not allow for any earthworks required to build up and shape the tailings surface.

TABLE 16

COVER COST ESTIMATE[1] FOR ALTERNATIVE COVER TYPES AND SITES

	COST/m^2 FOR ONTARIO SITE	SASKATCHEWAN WT SITE	SASKATCHEWAN SD SITE
1. No Cover			
(i) No action	-	-	-
(ii) Contour and direct vegetation			
Site preparation	0.75	1.00	1.00
Vegetation	2.50	.50	2.50
Total /m^2	3.25	1.50	3.50
(iii) Contour with pyrite free tailings and vegetation			
Site preparation	0.75	n/a	n/a
Pyrite removal and placement	*	n/a	n/a
Vegetation	0.50	n/a	n/a
Total /m^2	1.25 plus cost of producing and placing pyrite free tailings		
2. Thin Covers			
(i) Soil cover			
Site preparation	0.25	0.50	0.50
Till cover	1.67	2.34	2.34
Vegetation	0.50	0.50	0.50
Total /m^2	2.42	3.34	3.34
(ii) Rock cover			
Site preparation	0.25	0.50	0.50
Rock cover	3.00	2.34	2.34
Total /m^2	3.25	2.84	2.84
3. Thick Covers			
(i) 3 m soil or rock waste			
Site preparation	0.25	0.50	0.50
Till cover	7.50	10.50	10.50
Vegetation	0.50	0.50	0.50
Total /m^2	8.25	11.50	11.50
(ii) 3 m zoned cover			
Site preparation	0.25	0.50	0.50
Bottom layer	3.50	10.00	10.00
Middle layer	3.50	5.25	5.25
Upper layer	2.50	1.75	1.75
Vegetation	0.50	0.50	0.50
Total /m^2	10.25	18.00	18.00

1. Does not allow for any earthworks required to build up and shape the tailings surface.

*Cost not available

3.0 DISCUSSION OF ALTERNATIVE COVER TYPES FOR CANADA

3.1 GENERAL

In this section the effectiveness and cost benefit of the various alternative cover types is discussed. Table 17 presents a summary of the evaluation of the potential for long term instability for the various cover types and hence the potential for unacceptable release rates. It is apparent from this table that gully erosion, infiltration and frost heave represent the greatest concern with respect to long term stability.

Stable vegetation covers, with or without thin soil or rock covers do much to stabilize both the generic Elliot Lake and Saskatchewan Wet Tailings Sites. Thick covers appear to be necessary for the generic Saskatchewan Semi-Dry Site.

3.2 VEGETATION COVER

The stability analyses performed in this study have demonstrated the effectiveness of forest type cover to stabilize Canadian uranium tailings impoundments with respect to sheet and wind erosion, salt migration, infiltration and frost heave. It appears to do little for radon emanation and root activity may be responsible for the long term failure of drainage layers or suction barriers.

The cost of vegetation establishment is moderate and cost effective except where high lime consumptions may be required for long term soil conditioning.

The largest risks of permanent forest cover loss are due to ponding of surface waters and acid generation or salt migration. Considerable uncertainty still exists as to the potential for stable forest vegetation establishment and maintenance on acid generating tailings. This is a topic worthy of considerable further investigation.

3.3 WASTE ROCK/RIPRAP COVER

Waste rock, where available, is cost effective for the stabilization of covers against sheet and wind erosion. It is also the only reliably control for gully erosion. When used as a surface layer it increases infiltration and does little for frost heave or radon emanation.

Mine waste is not available in substantial quantities at the Elliot Lake mines and this would require drilling and blasting of materials specially for this purpose. In view of the disadvantages associated with increased infiltration as well as the higher cost, it is considered that vegetation stabilized thin soil covers are potentially more cost effective in the Elliot Lake region than are riprap covers.

At the Saskatchewan Wet Tailings Site, rock waste covers could potentially be used in combination with natural forest vegetation to provide a cost effective solution. The main concerns of frost heave, gully erosion and infiltration would be reduced by the forest vegetation.

TABLE 17

SUMMARY OF EVALUATIONS OF POTENTIAL INSTABILITY OF IMPOUNDMENT SURFACES

COVER TYPE	Cover Cost $/m^2	MODE OF INSTABILITY: Sheet Erosion	Gully Erosion	Wind Erosion	Salt Migration	Differential Settlement	Infiltration	Frost Heave	Radon Emanation
A. GENERIC ELLIOT LAKE SITE									
(i) no cover action	-	s	s	s	M	m	s	m	s
(ii) contour and revegetate	3.25	m-M	s	M	m-M	m	M	m	M
(iii) 1 m pyrite free tailings and vegetation	x +1.25	m-M	s	m-M	m-M	m	M	m	m
(iv) 600 mm soil cover	2.42	m-M	s	m-M	m-M	m	M	m	m
(v) 600 mm rock cover	3.25	m	M	m	M	m	s	m	m
(vi) 600 mm water cover	?	n	n	M-s	n	m	s	m	m
(vii) 3 m soil cover	8.25	m	M	m	m	m	M	m	m
(viii) 3 m zoned cover	10.25	m	M	m	m	M	M	m	m
(ix) 3 m water cover	?	n	n	n	n	m	s	n	m
B. GENERIC SASKATCHEWAN WT SITE									
(i) no cover action	-	s	s	s	m	m	s	s	s
(ii) contour and revegetate	2.5	m	s	m	m	m	M	M	M
(iii) 600 mm soil cover	3.34	m	s	m	m	m	M	M	m
(iv) 600 mm rock cover	2.84	m	M	m	m	m	s	M	M
(v) 3 m soil cover	11.50	m	M	m	m	m	M	m	m
(vi) 3 m zoned cover	18.00	m	m	m	m	M	M	m	m
C. GENERIC SASKATCHEWAN SD SITE									
(i) no cover action	-	s	s	s	s	m	M	s	s
(ii) contour and revegetate	3.50	s	s	s	s	m	M	s	s
(iii) 600 mm soil cover	3.34	M	s	M	M	m	M	s	M
(iv) 600 mm rock cover	2.84	m	M	m	s	m	M	s	s
(v) 3 m soil cover	11.50	m	M	m	m	m	M	m	m
(vi) 3 m zoned cover	18.00	m	M	m	m	M	M	m	m

Key

1. Potential Instability Code

   n = none
   m = minor
   M = Moderate
   s = severe
   N = not applicable

2. x = cost of producing pyrite free tailings

Remarks

Stability of vegetation questioned. Evaluation assumes success. Feasibility and cost (x) of producing pyrite free tailings unknown.

Direct vegetation presumed inappropriate. Evaluation assumes failure.

At the Saskatchewan Semi-Dry Tailings Site, the potential acid generation and phytotoxicity of the tailings may effectively prevent forest revegetation, and concerns regarding salt migration, frost heave, and radon emanation are severe. Moderate concerns remain regarding infiltration and gully erosion.

3.4 SOIL COVER

In the absence of forest vegetation, thin soil covers are expected to erode well within the 1000 to 2000 year period of concern. With stable forest cover they are considered to be a cost effective cover type. The main long term concern of forest stabilized thin soil covers is the potential for gully erosion. A moderate level of concern is associated with the infiltration that it will permit, and with frost heave at Saskatchewan sites.

Forest stabilized thin soil covers may be a suitable and effective cover at the Saskatchewan Wet Tailings Site.

At the Elliot Lake and Saskatchewan Semi-Dry sites (SD) it is not known with any confidence whether stable forest cover can be maintained on a thin soil cover. It is considered that with appropriate preparation, such cover could be successful at Elliot Lake but may not be possible or effective at the SD site.

Thick soil covers (or waste rock covers) would be effective at all sites. Gully erosion and infiltration are the only mechanisms of instability considered of moderate concern in the long term. The costs of such cover types are high when compared with the thin alternatives. The gain in long term security is not commensurate with the increase in cost but may be necessary in the case of tailings typical of the SD site.

3.5 WATER COVER

This study has been directed principally towards soil covers. Water covers have been included only as a comparison and because of the fairly recent realization of the potential effectiveness of such covers for Canadian conditions.

Thin water cover (less than the lake freezing depth) is considered entirely inappropriate. Ice drift and wedging would cause large releases at the impoundment edges.

Thick water covers (2-3 m) are considered very advantageous provided appropriate other site specific conditions can be met, such as:

- the cover does not induce unacceptable seepage
- the minimum cover depths will be maintained in drought periods
- the water retention structures required to maintain the water cover are stable in the long term

- the spillway structures which decant the excess water are stable when subject to the flood flows that will occur in the long term.

The design of water covers has not received much attention. It is anticipated that combinations of thin rock waste or soil covers under thick water covers will provide very effective tailings containment.

3.6 OTHER CONTROL MEASURES

3.6.1 Chemical Stabilization

The chemical stabilization of pyrite oxidation in Elliot Lake tailings is considered a most advantageous form of control. Possible on theoretical chemistry grounds, this form of control technology requires considerable research to determine if it can be developed into a feasible and economically acceptable technology.

Chemical stabilization takes the form of adding phosphate and silicate chemicals (possibly waste forms as opposed to pure chemicals) to a tailings slurry prior to deposition. By chemical interaction with the surface of the pyrite particle, an inactive coating is formed around the particle which prevents further oxidation. In the case of a phosphate chemical, a coating of iron phosphate is formed. Prior to the discovery that phosphate or silicate chemicals could inhibit pyrite oxidation, the use of agricultural limestone had been widely regarded as a means of inhibiting oxidation. Strictly speaking limestone did not inhibit the pyrite oxidation reaction but retarded the reaction and was itself consumed by the acidity produced by the reaction. Its inhibiting action was not therefore of a permanent nature.

The use of phosphate chemicals has been demonstrated on both a laboratory basis and a field trial basis for coal mine spoils in the eastern United States. Phosphate chemicals are still largely unknown factors for preventing pyrite oxidation in Canadian mill tailings in general and uranium mill tailings in particular. Limited research work undertaken in Canada on a variety of massive sulphide mill tailings has shown that the inhibition principle can apply to mill tailings. However, the effectiveness of phosphate (and silicate) chemicals is very variable and while relatively successful in the short term for several mill tailings, the long term effectiveness, as would be required for the abandonment of uranium mill tailings, is as yet unknown.

3.6.2 Surface Preparation

The preparation of the tailings surface, prior to the placement of the cover, is an important aspect of the cover design.

- o Drainage is required to improve trafficability and access.
- o Surface reshaping is necessary to provide uniform drainage and to reduce the tendency for water flows to concentrate and cause erosion.
- o Surface slopes must be such that, following consolidation of the tailings, surface drainage is maintained and ponding is prevented.

- o Riprap armoured drainage ditches may be required to drain water from low spots or where natural concentrated flows occur.

- o Chemical or physical conditioning of the tailings surface may be required prior to placing the cover.

These measures may represent a substantial proportion of the cover construction costs. In estimating the costs of the cover placement for the generic sites, it has been assumed that through the adoption of appropriate tailings placement methods, surface geometry was achieved which required only a minimum of surface preparation.

3.6.3 Infiltration Control

Net infiltration can be reduced by either establishing a vegetative cover, particularly a forest cover, or by installing a low permeability infiltration barrier. The evaluation done in this study indicates that in the absence of a drainage layer above the infiltration barrier, that such barriers are not very effective. In fact they may do more harm than good as a result of groundwater mounding on them, causing saturated soil conditions which prevents forest cover development. On fine grained tailings (such as at the SD site) a suction breaker layer may also be required to prevent high suction gradients through such layers.

Where forest cover can be established in Saskatchewan, there may be little, if any, advantage in a low permeability barrier.

3.6.4 Salt Migration Barriers

The installation of high permeability layers to limit the upward migration of salts may be advantageous on the acid generating tailings deposits (Elliot Lake and SD sites) where such migration could prevent stable forest cover. (Note: upward salt migration may not be a problem at Elliot Lake sites.) With such layers below thin forest stabilized soil covers, a high degree of long term stability may be achieved. The loss of barrier effectiveness due to root penetration may limit the long term effectiveness of such barriers.

3.6.5 Radon Barriers

Because of the low radon emanation rates and the remote locations of many of the Canadian tailings deposits, there may not be a need for radon emanation control. Where control is required, this cannot be provided by vegetation alone or by thin waste rock layers. Except possibly, in the instance of tailings from high grade ore deposits, thin soil (till) covers should be adequate and there seems to be no need for the elaborate, specially constructed radon barriers required in the U.S.A.

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